NC ROADWAY LIGHTING NEEDS ASSESSMENT, MAINTENANCE PRIORITIZATION TOOL AND PERFORMANCE MEASURES

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16. Abstract

The objectives of this project are to 1) develop an assessment report and summary of accumulated modernization / replacement needs, 2) assess current lighting needs and develop a method to allocate funds at NCDOT Division level, 3) research and document if installation of Light Emitting Diode (LED) luminaires instead of High Pressure Sodium (HPS) luminaires will yield benefits, 4) research privatization / outsourcing options, 5) research and develop an improved mechanism to prioritize interchange locations that require lighting, and, 6) recommend an improved warranting criteria with operational and performance measures.

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Specifications and cost estimates for design, equipment, installation or maintenance used in this research study are based on project bids and informal quotes obtained from certain manufacturers. They vary from one manufacturer to another and cannot to be considered as a uniform standard or purchase price.

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EXECUTIVE SUMMARY

North Carolina has massive State owned lighting systems spanning over a 2,700 center-lane mile highway system (comprising Interstate, US, NC and State secondary routes with full and partial access control). Much of North Carolina's lighting systems are at interchanges along heavily traveled freeways. These lighting systems are aging and are in need of modernization / upgrade. The current maintenance needs exceed available resources making it even more difficult to maintain, modernize and meet public expectations. The objectives of this project are to 1) develop an assessment report and summary of accumulated modernization / replacement needs, 2) assess current lighting needs and develop a method to allocate maintenance funds at North Carolina Department of Transportation (NCDOT) Division level, 3) research and document if the installation of Light Emitting Diode (LED) luminaires instead of High Pressure Sodium (HPS) luminaires will yield benefits, 4) research privatization / outsourcing options, 5) research and develop an improved mechanism to prioritize interchange locations that require lighting, and, 6) recommend an improved warranting criteria with operational and performance measures.

Two methods are proposed to assess lighting needs and allocate maintenance funds (includes for modernization / upgrade) between Divisions in the state of North Carolina. The first method is based on the percent of population, the percent of lighted interchanges and the percent of night-time crashes on full access controlled and partial access controlled facilities while the second method is based on the percent of population, the percent of lighted interchanges and the percent of total crashes on full access controlled and partial access controlled facilities in each Division. Both the methods yielded similar results (trends). However, marginal difference in funds allocated to the Divisions was observed based on the two methods. Based on the methods, resources allocated for maintenance of lighting systems are highest for Division 10 followed by Divisions 5 and 7. As night-time crashes have higher relevance to roadway lighting, method 1 is recommended for allocation of resources at Division level.

A cost benefit analysis was conducted to evaluate if replacing HPS luminaires with LED luminaires would yield benefits. The results obtained show that replacing a 250 watt

(W) HPS luminaire with up to a 105 W LED luminaire would yield economic benefits while replacing a 400 W HPS luminaire with up to a 215 W LED luminaire would yield economic benefits. Disruption to traffic along with related delay costs and personnel costs associated with maintenance were ignored in the economic analysis. Considering these would result in increased costs for HPS luminaires and make the use of LED luminaires a more economically viable option. Further, LED luminaire costs are expected to decrease while energy consumption costs are expected to increase in the future. This will make the use of LED luminaires for roadway lighting even more cost-effective in the future. In general, using a suitable lower wattage of LED luminaire would maximize benefits for NCDOT when replacing HPS luminaires with LED luminaires.

Research was done to determine the most suitable and economic option for construction, design and maintenance of roadway lighting in North Carolina. Results obtained indicate that current practice (base case) of roadway lighting design and maintenance by NCDOT and construction by private firms is an equally viable option as maintenance by NCDOT and roadway lighting design and construction by private firms. Roadway lighting design by NCDOT and construction and maintenance by private firms is as economical as privatizing design, construction and maintenance of roadway lighting systems. Adopting any of these above two scenarios would result in a marginal increase in costs to NCDOT. The results from sensitivity analysis (10% increase or decrease in costs) support those obtained from economic analysis. A 10% decrease in NCDOT construction cost (if the private firm construction cost remains constant) may bring down the total cost to lower than the base case. The benefits, however, in this case are marginal. On the other hand, obtaining competitive bids and lowering private firm construction cost will lower the overall cost and maximize benefits to NCDOT

Data was collected at 80 interchanges (38 with lighting system and 42 without lighting system) along nine corridors to identify new factors, unlighted and lighted weights and update the “Total Design Process (TDP)” prioritization tool. The new factors identified and included in the updated tool are acceleration lane length, deceleration lane length, distance of signboard placement from the interchange, crashes by severity, illumination level, the percent of heavy vehicles at night and ramp volume ratio. Acceleration lane length and deceleration lane length less than 250 ft, signboard placement distance less than 1,320 ft, lower luminous index, and an increase in the percent of heavy vehicles and ramp volume ratio all tend to increase risk to drivers at interchanges. Analysis based on crash data indicate that night-to-day crash rate ratio is less than 3 for 35 interchanges with lighting system and 37 interchanges without lighting system. It was observed to be greater than 3 at 2 interchanges with lighting system and 4 interchanges without lighting system. These interchanges with night-to-day crash rate ratio greater than 3 have a relatively fewer numbers of crashes. Also, most of the crashes at interchanges with night-to-day crash rate ratio greater than 3 (or night-to-day crash ratio greater than 1) are less severe injury or property damage only (PDO) crashes. A comparison of computed warranting points using both the current and updated tools indicate a decrease in warranting points at these interchanges using the updated tool. In general, warranting points using the updated tool increased for interchanges with more severe crashes. Therefore, it is recommended to consider the number of crashes by severity instead of night-to-day crash rate ratio for prioritization of lighting system installation or maintenance.

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CHAPTER 1. INTRODUCTION

Transportation statistics indicate that hardly 25% of travel occurs at night (dark light conditions or say, typically between 7 PM and 6 AM). However, more than 50% of fatalities occur during this time period (NHTSA, 2010). In 2009, nationally, 14,488 (47%) fatal crashes were reported under dark light conditions, 14,948 (48.5%) were reported during daylight conditions and 1,222 (3.47%) were reported during partial lighting conditions (dawn/dusk) in the United States. During the same period, North Carolina has seen 1,345 (69.4%) fatal crashes at night or under partial lighting conditions. Inadequate roadway lighting in addition to factors such as fatigue, driving under the influence of alcohol or drugs, inattentive driving, speeding and failure to reduce speed are most common contributing factors of crashes at night.

1.1. Introduction

Roadway lighting and sign illumination plays a vital role in reducing night-time crashes by providing visibility and comfort for drivers, pedestrians, bicyclists and transit users. It is an important component of the transportation system. Improved visibility through illumination increases the probability of an average driver to aptly identify and react to the hazard and take appropriate action while driving at night (AASHTO, 2005). However, imbalance between the available resources and the number of center-lane miles of roadway network that warrants lighting has limited the agencies from installing improved roadway lighting systems throughout the roadway network.

The United States Department of Energy (DOE) has estimated that 26.5 million streetlights in the United States consume as much electricity each year as 1.9 million households, and generate greenhouse gas (GHG) emissions equivalent to that produced by 2.6 million cars (Peters, 2012). An estimated 8.1 Terawatt hours (TWh) of total annual energy savings could be achieved by replacing nationwide stock of installed High Pressure Sodium (HPS) roadway luminaires with Light Emitting Diode (LED) luminaires that perform well in the field, with a corresponding 5.7 million metric tons of $CO2$ emissions abated (Cook et al., 2008a). A thorough evaluation of current needs, adopted priority index tool, technology options and maintenance / upgrade alternatives is therefore required.

1.2. Need for Research

Improved roadway lighting is one strategy considered and well perceived by travelling public for safe and comfortable night-time use of roadway network. Several researchers in the past have shown that roadway lighting or illumination can help reduce night-time crashes on roads (Walker and Roberts, 1976; Lipinski and Wortman, 1978; Schwab et al., 1982; Elvik, 1995; Preston and Stoenecker, 1999; Hasson and Lutkevich, 2002; Elvik and Vaa, 2004; Isebrands et al., 2004, 2006; Breanuea and Morin, 2005; Harwood et al., 2007; Wanvik, 2009; Rea et al., 2009). However, it is very expensive to install the hardware for required or additional lighting. The maintenance and utility charges associated to roadway lighting can often be a costly bet for smaller jurisdictions (Hallmark, 2008).

North Carolina's Roadway Lighting Committee (as stated in their Division Assessments & Needs Report, December 2005) has acknowledged the deteriorating state of the lighting system in North Carolina. With massive State owned lighting systems, North Carolina has accumulated needs in excess of $25 million of obsolete, malfunctioning and deteriorating lighting systems to install, maintain, and upgrade lighting on ~2,764 center-lane mile highway system (comprising Interstate, US, NC and State secondary routes with full and partial access control). The current needs exceed available resources making it difficult to meet the public expectations. Further, the lighting systems are aging and are in need of modernization / upgrade. Concerns have been expressed by the staff of North Carolina Department of Transportation (NCDOT) "with continuing to construct new systems and the likely scenario being one of very limited to no maintenance and ultimate system failure / shut down in the future."

The decision to add lighting along full access controlled facilities as a part of a new roadway construction project in North Carolina is made by the Lighting Committee after the project is evaluated and justified for lighting, with input from the Division. Funding, in this case, is secured by the Lighting Committee. On the other hand, resources are allocated to each Division for maintenance and upgrade of roadway lighting along full access controlled facilities. The allocation of resources (budget) for roadway lighting system maintenance and upgrade on these facilities depends on potential benefit (population, traffic volume or vehicle miles traveled), the number of interchanges with lighting and risk to drivers at night (crash involvement). However, there is no method or process currently available or adopted to assess needs at NCDOT Division level and allocate funds for improved roadway lighting systems in North Carolina.

Land use is a part of the current prioritization tool for installation of new lighting systems. Quadrant development is considered for interchanges, while overall percent development along the roadway is considered for continuous roadways. Providing lighting at obsolete sections because of poor conditions and no traffic at night (due to closure of business or change in land use) is cost prohibitive. The concept "lighting curfews" (TxDOT, 2010), which refers to turning-off or reducing the amount of roadway lighting (trimming and dimming) during certain portions of the night when traffic volumes are low, may help reduce costs under such circumstances. Probable turning-off, trimming or dimming of lighting at locations (where businesses are closed, land use has changed or at locations with low night-time traffic volume or during certain portions of night) might result in substantial cost savings. The cost-effectiveness, however, depends on the investment in equipment required to obtain the dimming/trimming capabilities. The significant investment in equipment for dimming and trimming could result in a long payback period. In addition, the new standards (retro-reflectivity) for signs may not require lighting for certain sign types. This could also reduce costs. However, these aspects have not been researched much nor were considered in the prioritization process in the past.

As stated in the NCDOT Research Problem Statement, "the lack of consistency, low business priority, and perception of marginal public safety and security benefit have relegated these life saving freeway features into a quagmire of deterioration with no mechanism or priority for modernization, replacement, phase out, or repair. The deteriorated systems waste energy, requires recurrent maintenance, provide marginal to poor lighting for traveler navigation, and place a recurrent drain on very limited traffic services budgets." Also, parts may not be available to replace old, obsolete and deteriorating lighting systems. There is a need to research and identify lighting systems that are more durable, suitable for North Carolina conditions, and result in low installation, maintenance and life cycle costs. These lighting systems such as LED luminaries have to be compared with traditional HPS luminaries to evaluate their effectiveness in terms of energy consumption, compatibility, environmental benefit, safety benefit and driver perception prior to large-scale implementation or replacement.

Resource limitations, in general, have led public agencies to explore public private partnerships (PPP) or hire private firms to work on projects and meet their desired goals. NCDOT currently designs and maintains interchange lighting systems while construction is done by a private firm or contractor. Privatizing design in addition to construction of interchange lighting systems may be an equally viable or economical option. There is a need to research these as well as other options to find out if privatizing design, construction and maintenance of interchange lighting systems will result in monetary benefits.

As stated previously, the current lighting system needs exceed available resources. Agencies throughout the United States, including NCDOT, rely on National Highway Cooperative Research Program (NCHRP) Report 152 “Warrants for Highway Lighting” (Walton and Rowan, 1974) and the updates that followed this effort to identify and prioritize lighting needs along roadway sections. However, this more than 30 year-old guidebook does not account for various factors that range from safety to traffic composition and other design criteria (example, acceleration and deceleration lane lengths) that are essential for allocation of limited available resources. There is a need to research current practices (in North Carolina as well as in other states), update the state of knowledge, and develop an improved mechanism to prioritize roadway sections that require better and enhanced lighting needs.

Addressing the above discussed needs and past limitations through proposed research will not only help in better driver navigation but also leads to safety, comfort and convenience for drivers during adverse weather conditions and night-time travel. The developed mechanism and prioritization process would help NCDOT in better utilization of their limited resources.

1.3. Research Objectives

The objectives of the proposed research project, therefore, are to

1) develop an assessment report and summary of accumulated modernization / replacement needs,
2) assess current lighting needs and develop a method to allocate funds at NCDOT Division level,
3) research and document LED luminaires potential,
4) research privatization / outsourcing options,
5) research and develop an improved mechanism to prioritize interchange locations that require lighting, and,
6) recommend an improved warranting criteria with operational and performance measures.

1.4. Organization of the Report

The remainder of this report comprises 6 chapters. A review of existing literature on benefits of roadway lighting, roadway lighting warrants, prioritization tools used in the past, and studies on privatization and outsourcing options are discussed in Chapter 2. An assessment at Division level is discussed in Chapter 3. Research and documentation on the effectiveness of LED luminaires as possible replacement for existing HPS lighting systems is presented in Chapter 4. Research on privatization and outsourcing options for roadway lighting at interchanges is discussed in Chapter 5. Data collection, additional factors and improved mechanism to prioritize interchange locations that require lighting is presented in Chapter 6. Conclusions from this research are presented in Chapter 7.

CHAPTER 2. LITERATURE REVIEW

Improving safety, visibility and security are the primary objectives of roadway lighting at intersections, freeway/highway interchanges, at pedestrian crossing locations and along transit corridors. The need for roadway lighting depends on site specific variables pertaining to the geographic location. While it is widely known and accepted that improved lighting increases safety, it is practically not feasible to provide lighting on all roadways and at all points in the road network due to huge installation and life cycle costs involved. A review based on findings from previous studies on need for / benefits of lighting, past and current practices/guidelines, an update on maintenance and life cycle costs, prioritizing roadway sections that require lighting, comparison of HPS and LED luminaries by researchers and practitioners in the past, and privatization and energy conservation methods adopted by other agencies is presented in this chapter.

2.1. Need for Roadway Lighting

A summary of factors that emphasize the value of roadway lighting, in general, include the following (AASHTO, 2005; Walton & Rowan, 1972).

- Traffic volume and crashes (typically, high crash and high volume segments/locations);
- High pedestrian activity locations such as downtown, commercial and tourist attraction centers, and transit corridors;
- Geometric orientations such as skewed and at-grade intersections, ramps and ramp terminals;
- Poor visibility roadway segments such as curved segments, underpasses with low sight distances, isolated rural intersections and undivided roadway segments;
- Locations that do not meet lighting design warrants/guidelines;
- Areas or locations with high crash rates at night (for security purposes);

2.2. Benefits of Roadway Lighting

As stated previously, several researchers in the past have found that roadway lighting or illumination helps reduce night-time crashes on roads (Walker and Roberts, 1976;

Lipinski and Wortman, 1978; Schwab et al., 1982; Elvik, 1995; Preston and Stoenecker, 1999; Hasson and Lutkevich, 2002; Elvik and Vaa, 2004; Isebrands et al., 2004, 2006, 2010; Bruneau and Morin, 2005; Harwood et al., 2007; Wanvik, 2009; Rea et al., 2009). Table 1 summarizes percent reduction in vehicular crashes observed after the installation of roadway lighting from the selected studies.

Author	Location	% Reduction in Vehicular Crashes
Elvik (1995)	Eleven Countries	65 (fatal night-time crashes)
Preston and Stoenecker (1999)	Rural Intersection	40 (night-time crashes)
Green et al. (2003)	Intersection	45 (average night-time crashes)
Bruneau and Morin (2005)	Rural Intersection	39 (night-time crash rate)
Siddiqui et al. (2006)	Florida (Pedestrian Crashes)	54 (night-time fatal pedestrian crashes)
Wanvik (2009)	Dutch Roads	53 (fatalities in dark conditions)
Isebrands et al. (2010)	Rural Intersection	37 (night-time crash rate)

Table 1. Benefits of Roadway Lighting – % Reduction in Vehicle Crashes

Gramza et al. (1980) analyzed the safety benefits of roadway lighting at rural interchanges using the Interstate System Accident Research (ISAR-2) data for 10 years. The crashes were categorized into seven types and illuminance was a factor of influence for two categories. Models were developed to predict the frequency of night-time crashes based on the night-time traffic volume, geometry of the interchange and location. A reduction of 43% in crashes was observed at interchanges considered in their study.

Bruneau et al. (2001), in their study on continuous and interchange lighting, revealed that there is no significant difference between partial and full lighting at interchanges. However, there is a considerable difference between interchange lighting and no lighting.

Bruneau and Morin (2005) compared night- and day-time crash rate ratio at rural intersections using student p-test at a 5% significance level. The study considered three categories of severity: fatal/personal injury, property damage and all crashes. It was observed that non-standard lighting and standard lighting reduced night-time crash rate ratios by 29% and 39%, respectively.

Monsere and Fischer (2008) observed that the total number of night-time crashes increased by 2.46% when roadway lighting was reduced to partial lighting from full lighting. However, injury night-time crashes decreased by 12.16% at the same locations. At locations where partial plus lighting (defined as level of lighting between partial and full lighting by the authors) was reduced to partial lighting, a reduction of 35.24% in total crashes as well as a reduction of 39.98% in injury night-time crashes were observed.

Rea et al. (2009) concluded that the installation of roadway lighting reduces the number of night-time crashes. Their research also provided insights on methodologies to quantify the impact of lighting and other effects such as on economic development and light pollution.

Bullough et al. (2009) conducted a simulated analysis of visual performance of drivers under different lighting conditions. Their study found that safety potential hazards/dangers can be better located by the driver under improved lighting conditions. The simulations conducted in their study were based on photometric accurate lighting software. Their conclusions strengthen the belief that elderly drivers and distracted drivers can benefit from lighting in terms of safety.

Donnel et al. (2009) compared expected night-to-day crash ratios, frequencies and severities computed from negative binomial regression and log-linear models to those computed directly from crash data. Site specific variables such as geometric design, traffic control device and presence of roadway lighting were also included as variables in the models. An improvement in safety was observed at intersections with fixed lighting when compared to those without lighting. However, it was mentioned that statistically significant improvements could not be observed due to enhanced lighting at interchanges and along freeway segments.

The installation of roadway lighting could improve security and reduce crime rate. Painter et al. (1997) found that crime rate reduced by 41% when the roadway lighting systems were installed at a location. Farrington and Welsh (2002) measured the effect of improved roadway lighting on crime and concluded that there was a 20-30% reduction in crime after the installation of roadway lighting. Rea et al. (2009) presented a comprehensive discussion on the effects of roadway lighting on crime and fear of crime.

The role of roadway lighting on pedestrian safety has also been researched in the past. Painter (1996) studied the influence of roadway lighting on pedestrian activity along three poorly lit and potentially dangerous streets. The study concluded that improved roadway lighting not only reduces crime rate but also increases pedestrian usage remarkably. Edwards and Gibbons (2008) studied the illuminance level required for safe crossing of pedestrians at crosswalks. The study revealed that vertical illumination with illuminance level of 20 lux would be the best practice. Wanvik (2009) studied various effects of roadway lighting at rural intersections and concluded that safety effects due to roadway lighting are significantly larger for pedestrians than automobiles. The pedestrian crashes reduced by 72% after the installation of roadway lights.

While there are several benefits due to lighting, negative effects such as glare, energy consumption and light pollution have to be taken into account in the decision making process.

2.3. Past and Current Practices/Guidelines

Roadway lighting is a proven measure to increase safety, reduce crime and improve ambience besides having other benefits such as increased economic activity and efficient movement of people during night-time. Lighting systems are expected to reveal the roadway and its surroundings to the road user without causing discomfort to the eyes. While horizontal illumination is measured to quantify lighting on roads, uniformity ratio is used as a qualitative measure. The level, quantity and area of luminance required are discussed in AASHTO’s “Roadway Lighting Design Guide, 2005” and Illuminating Engineering Society of North America (IESNA)’s “American National Standard Practice for Roadway Lighting, 2000”. These are the two guides used extensively in the United States. AASHTO (2005) supplements the 1984 publication titled “An Informational Guide for Roadway Lighting”.

AASHTO (2005) and NCHRP Report 152 (Walton and Rowan, 1974) provide several warranting and screening methods to assess and identify potential locations that require roadway lighting to improve safety. The NCHRP Report 152 emphasizes on various geometric, operational and environmental conditions, while AASHTO emphasizes on exposure or average daily traffic (ADT).

AASHTO's guide, in general, provides information on master lighting plans, techniques of lighting design such as uniformity of illuminance and luminance considerations, warranting conditions, design values for freeways and other roadways, pole placement guidelines, guidelines for tunnels and underpasses, work zone and temporary roadway lighting, roundabouts, rest areas, and electrical system requirements. Tables 2 and 3 summarize AASHTO warrants for complete interchange lighting (CIL) and partial interchange lighting (PIL), respectively.

"NCHRP Report 152: Warrants for Highway Lighting, 1974" is generally used for assessing lighting needs. According to the recommended method (Table 4), the minimum warranting condition is the total effectiveness achieved by lighting a traffic facility with an average rating of 3 on the subjective scale of 1 to 5 for each classification factor (geometric, operational, environmental and night-to-day crash rate ratio). The minimum warranting condition for CIL is 90 points and for PIL is 60 points (also shown in Table 4). To calculate the number of points for a facility, the rating number for each factor is multiplied by the difference between unlighted weight (A) and lighted weight (B). All the points are then added and compared with the minimum warranting points required. It is generally agreed by practitioners that this more than 30 year old document lacks several needed updates.

Several states have their own guidelines for roadway lighting. Green et al. (2003) found that 14 out of 33 states surveyed had specific warrants not given in the AASHTO publication. Table 5 summarizes warrants used by selected states from their research. Out of the 19 states surveyed by Hallmark et al. (2008), only six states use AASHTO's guide or NCHRP 152 while all the remaining states have their own criteria to warrant lighting installations at rural intersections. Another survey conducted as part of a research study by Rea et al. (2009) showed that 80% of 37 states surveyed used AASHTO's guide while two-thirds of the respondents stated that IESNA's publications are helpful. The survey also found that information from other resources such as Federal Highway Administration (FHWA) guidelines on roadway lighting, recent research results, manufacturer information, and state requirements are also used by the respondents.

Case	Warranting Conditions
CIL - 1	Where the total current ADT ramp traffic entering and exiting the freeway within the interchange area exceeds 10,000 for urban conditions, 8,000 for suburban conditions, or 5,000 for rural conditions.
CIL - 2	Where the current ADT on the crossroad exceed 10,000 for urban conditions, 8,000 for suburban conditions, or 5,000 for rural conditions.
CIL - 3	Where existing substantial commercial or industrial development, which is lighted during hours of darkness, is located in the immediate vicinity of the interchange, or where the crossroad approach legs are lighted for ~0.5 miles (1 km) or more on each side of the interchange.
CIL - 4	Where the night-to-day ratio of crash rates within the interchange area is at least 1.5 or higher than the statewide average for all unlighted similar sections and a study indicates that lighting may be expected to result in a significant reduction in the night-time crash rate. Where crash data are not available, rate comparison may be used as a general guideline for crash severity.

Table 2. Warrants for Complete Interchange Lighting (CIL)
(Source: AASHTO Roadway Lighting Design Guide, 2005)

Case	Warranting Condition
PIL - 1	Where the total current ADT ramp traffic entering and exiting the freeway within the interchange area exceeds 5,000 for urban conditions, 3,000 for suburban conditions, or 1,000 for rural conditions.
PIL - 2	Where the current ADT on the freeway through traffic lanes exceeds 25,000 for urban conditions, 20,000 for suburban conditions, or 10,000 for rural conditions.
PIL - 3	Where the night-to-day ratio of crash rates within the interchange area is at least 1.25 or higher than the statewide average for all unlighted similar sections and a study indicates that lighting may be expected to result in a significant reduction in the night-time crash rate. Where crash data are not available, rate comparison may be used as a general guideline for crash severity.

Table 3. Warrants for partial interchange lighting (PIL)
(Source: AASHTO Roadway Lighting Design Guide, 2005**)**

Classification Factor	Rating 1	2	3	4	5	Unlit Weight (A)	Lighted Weight (B)	Diff (A-B)	Score Rating x(A-B)
Geometric Factors									
Ramp Types	Direct	Diamond	Button Hooks Cloverleaf	Trumpet	Scissors and left side	2.0	1.0	1.0	______
Cross-Road Channelization	none	-	continuous	-	at interchange intersections	2.0	1.0	1.0	______
Frontage Roads	none	-	one-way	-	two-way	1.5	1.0	0.5	______
Freeway Lane Widths	>12	12	11	10	<10	3.0	2.5	0.5	______
Freeway Median Widths	>40	34-40	12-24	4-12	<4	1.0	0.5	0.5	______
No Freeway Lanes	4 or less	-	6	-	8 or more	1.0	0.8	0.2	______
Main Line Curves	<½°	1-2°	2-3°	3-4°	>4°	13.0	5.0	8.0	______
Grades	3%	3-3.9%	4-4.9%	5-6.9%	7% or more	3.2	2.8	0.4	______
Sight Dist. Cross Road Intersection	>1000'	700-1000'	500-700'	400-500'	<400'	2.0	1.8	0.2	______
						Geometric Total			______
Operational Factors									
Level of Serice (any dark hour)	A	B	C	D	E	6.0	1.0	5.0	______
						Operational Total			______
Environmental Factors									
% Development	none	1 quad	2 quad	3 quad	4 quad	2.0	0.5	1.5	______
Set-Back Distance	>200'	150-200'	100-150'	50-100'	<50'	0.5	0.3	0.2	______
Cross-Road Approach Lighting	none	-	partial	-	complete	3.0	2.0	1.0	______
Freeway Lighting	none	-	interchanges only	-	continuous	5.0	3.0	2.0	______
						Environmental Total			______
Accidents									
Rate of night to day accident rates	<1.0	1.0-1.2	1.2-1.5	1.5-2.0	>2.0*	10.0	2.0	8.0	______
*Complete lighting warranted						Accident Total			______

Geometric Total ______
Operational Total ______
Environmental Total ______
Accident Total ______
Sum ______ Points

Complete lighting warranting condition 90 points
Partial lighting warranting condition 60 points

Table 4. NCHRP Report 152: Warrants for Highway Lighting Method

(Source: NCHRP Report 152: Warrants for Highway Lighting, 1974)

State	Warranting Conditions
Alabama	ANSI "Roadway Lighting" RP-8-00.
California	Freeway Interchange: • Total sum of ADT ramp volume for all four ramps exceeds 5,000 for urban, 3,000 for suburban, and 1,000 for rural area. • Freeway ADT exceeds 25,000 for urban, 20,000 for suburban, and 10,000 for rural areas. The state also follows certain warrants for intersection lighting and railroad grade crossing lighting.
Illinois	Uses AASHTO warrants for freeway lighting. But, for intersections few new warrants, which emphasize on geometry and traffic property of intersections, are used.
Indiana	Roadway lighting crash warrants analysis worksheet.
Iowa	The interchange lighting warrants are same as AASHTO's. The intersection lighting has few new warrants based on night-to-day crash rate ratio and traffic volume.
Kansas	Freeway interchange: Total sum of ADT ramp volume for all four ramps exceed 5,000 for urban, 3,000 for suburban and 1,000 for rural areas. The state also follows few warrants for continuous freeway and intersections based on night crashes, geometry and traffic volume.
Maryland	ANSI "Roadway Lighting" RP-8-00.
Minnesota	Complete interchange lighting if mainline has continuous lighting. Partial interchange lighting: • Total sum of ADT ramp volume for all four ramps exceeds 5,000 for urban, 5,000 for suburban, and 2,500 for rural area. • Freeway ADT exceeds 25,000 for urban, 20,000 for suburban, and 10,000 for rural areas. • Night-to-day crash rate ratio is at least 1.25 or higher than state average. The state follows certain warrants for continuous freeway and at grade intersection lighting based on ADT and crash rate.
Mississippi	Uses NCHRP Report 152 for special areas such as intersections on non-controlled access roadways.

State	Warranting Conditions
Missouri	Interchanges with lighting along major road if one of the following is met: • ADT on major road exceed 25,000 for urban, 20,000 for suburban, 10,000 for rural and the crossroad ADT exceeds 1,500. • Night-to-day crash rate ratio is at least 1.25. • Ramp ADT entering and leaving exceeds 5,000 for urban, 3,000 for suburban, and 1,000 for rural and the crossroad ADT exceeds 1,500. There are few warrants for continuous freeway lighting and intersections.
Montana	Few warrants for roads with raised median.
New Jersey	Few warrants for intersection lighting.
New York	Interchanges: • Night-to-day crash rate ratio is at least 2.5 provided 6 or more night-time crashes per year have occurred over a 3 year period. Roadway approaches to interchanges and ramps. The state follows a few warrants for continuous lighting and intersection lighting based on ADT and night-to-day crash rate ratio.
North Carolina	Interchanges and continuous sections determined by NCHRP Report 152 guidelines. In addition, partial lighting as a minimum for single point urban diamond interchanges and diverging diamond interchanges
North Dakota	Interchanges: • Ramp ADT entering and leaving exceeds 10,000 for urban, 8,000 for suburban, and 5,000 for rural areas. • ADT on crossroad exceeds 10,000 for urban, 8,000 for suburban, and 5,000 for rural areas. • Lighted commercial or industrial development in the vicinity of interchange or where the crossroad approach legs are lighted for 0.5 miles or more on each side of interchange. • Night-to-day crash rate ratio is at least 1.5 or higher than state average. Partial interchange: • Ramp ADT entering and leaving exceeds 5,000 for urban, 3,000 for suburban, and 1,000 for rural areas. • Freeway mainline exceeds ADT of 25,000 for urban, 20,000 for suburban, and 10,000 for rural areas. • Night-to-day crash rate ratio is at least 1.25 or higher than state average. • Local government finds sufficient benefit to pay 50% of the installation cost. Few extra warrants are followed for freeway, US and State Roads lighting as well as intersections.

State	Warranting Conditions
Oklahoma	Few warrants for streets and roadways other than freeways.
Oregon	Few warrants for access controlled roadways.
Washington	Few warrants based on geometry, night-time crash etc.
Wyoming	Interchange: • Geometric conditions • Traffic volume • Crash experience Few extra warrant for intersections based on roadway, geometric conditions, and traffic volume and crash experience.

Table 5. Warrants Used by Selected States – Summary
(Source: Green et al., 2003)

Both AASHTO (2005) and NCHRP Report 152 (Walton and Rowan, 1974) methods do not take changes in vehicle technology and sign retro-reflectivity standards into account. Other recommended methods found in the literature include an assessment based on ratio of the number of night-time crashes after and before lighting to the ratio of number of day-time crashes after and before lighting, safety ratios of lighted and unlighted locations, identifying point of diminishing returns, and ranking based on benefit-cost ratio of alternative methods. Likewise, safety related prioritization techniques include quantum of crashes method, crash-prone index and weighted severity index method, and weighted prioritization methods used by individual agencies for allocating funds to new transportation projects and maintenance programs.

Decker (1989) indicated that ADT, crash reduction factors and night-time crash rates per million are the most important parameters in prioritizing roadway lighting. The study includes a total of 10 parameters which are categorized into three groups based on benefits. Maximum allowable pole spacing, off-sets, lamp wattages, luminaires per pole and mounting heights are of lesser benefit. According to their study, little benefit is obtained by choosing pole types or anticipating interest rates.

Factors such as tourism, elderly drivers, traffic mix, volume-to-capacity ratio, total night-time volume, ADT and night-to-day crash ratio for similar unlit sections of roadway should be included to warrants in NCHRP Report 152 (Aronin et al., 2002). These new warrants would improve the current warrants as they address a variety of factors that were not included in the original report. Each factor has a rating from 1 to 5, of which a rating of 1 represents least severe condition. Their procedure then involves a benefit-cost analysis and graphical comparison to prioritize the locations where lighting is required.

Lambert and Turley (2003) developed screening methods using concepts derived from risk assessment and management with a theoretical foundation in benefit-cost analysis. The authors considered night-to-day crash rate ratios and traffic volumes to compare and assess the needs. The exposure assessment phase analyzed the potential crash reduction and costs of available lighting technologies followed by a site-parameter assessment phase to identify a set of engineering criteria to determine whether lighting would effectively reduce crashes. In the first phase (exposure assessment), benefit to cost ratio is calculated. Using different values for variables in the equation, a graph is plotted with night-to-day crash rate ratio versus ADT. The graph is divided into three areas: accepted (B/C > 1 for all ranges of input variables), marginal (B/C ~ 1 depending on variable values used), and rejected (B/C always < 1). If the needs fall in marginal or accepted region, the second phase (site parameter assessment) is carried out. The assessment is carried out with a more efficient and simplified method. Unlike the NCHRP Report 152 which uses four lists of twelve to twenty parameters, the new method has one unique list of eight parameters. These parameters are section/intersection geometry, traffic mix, vehicle conflict opportunities, posted speed, curves and grades, veiling luminance, level-of-service, and inter-modal transactions. Projects that pass both the assessments are nominated for a detailed benefit/cost analysis to determine the allocation of funding for fixed lighting improvements.

Isebrands et al. (2004) suggested that installing lighting at unlighted intersections is an effective safety countermeasure. They considered ADT, night-to-day crash ratio and the number of crashes per million entering vehicles (MEV) as factors for prioritization of lighting in their study.

Hallmark et al. (2008) presented a methodology to help local agencies decide when and where to provide rural intersection lighting to reduce night-time crashes. They conducted safety evaluation of 223 rural intersections to demonstrate the cost-effectiveness of lighting and other low cost treatments and to evaluate rural intersections with and without lighting to assist local agencies in the decision making process.

Alternative low cost measures for lighting did not prove to be more effective than roadway lighting in their research.

More recently, Rea et al. (2009) worked to develop guidelines to determine appropriate roadway lighting for existing and planned facilities for safety benefits as a part of the NCHRP Project 05-19 conducted by Rensselaer Polytechnic Institute, New York.

A scaled weighting prioritization method can best address the allocation of limited resources based on crashes, traffic volume, area type, functional classes and land uses. The fatal crashes have relatively more societal costs than a severe injury, less severe injury or property damage only (PDO) crashes to no crash. Likewise, downtown areas are rated higher than rural areas in terms of activity (traffic volumes and economic activity), but some locations in rural areas might need more attention from a safety point of view. Commercial-center land uses will benefit more due to increased economic activity during night-time with roadway lighting in place. However, safety near residential land uses might be of more priority than other land uses. Research should be conducted to identify land uses, area types for certain combinations of night-time traffic and crash rates that require attention from a safety perspective. Benefit-cost analysis should be performed for maintaining and installing new roadway lighting. While prioritizing lighting needs, sections with installed roadway lighting have sunk costs in terms of installation and only the maintenance and life cycle costs should be considered in such cases.

2.3.1. Benefit-Cost Analysis

Providing lighting to a large transportation network is cost prohibitive with other maintenance programs and new roadway projects fighting for limited resources. The cost of equipment, installation, maintenance and corresponding life cycle cost of lighting systems are also substantial. New or continuing maintenance of lighting installations can be justified if the societal (crash/crime) costs outweigh the lighting costs.

Benefit-cost analysis have been conducted by several authors (Janoff and McCunney, 1979; Box, 1989; Preston and Schoenecker, 1999; Painter and Farrington, 2001); Deans et al., 2003; Lambert and Turley, 2003; Rea et al., 2009) to assess the benefits of lighting installations. The 1996 FHWA Annual report to Congress, covering 1974-

1995, indicated that illumination will have a benefit to cost ratio of 26.8 and ranked highest of all roadway safety improvements (FHWA, 1996).

Preston and Schoenecker (1999) valuated the cost of crashes before and after the installation of roadway lighting. The cost of crashes was obtained from Minnesota Department of Transportation. The crashes were classified as fatal, personal injury (type A, B, C), and PDO crashes with fatal having the highest cost and PDO crash having the lowest cost. The cost of crashes after the installation was subtracted from the cost of crashes before the installation to find the benefit. The cost of installation, operation and maintenance was summed up to get the total cost. The benefit to cost ratio was calculated and ratio greater than 1 was said to be beneficial.

Lambert and Turley (2003) considered several variables to define the benefit to cost ratio that was used to justify roadway lighting at a location. The benefit to cost ratio was defined as the ratio of the expected cost of the night-time crashes avoided per mile per year and the cost of lighting per mile per year. It was expressed as

$$\text{Benefit to Cost Ratio} = \frac{365 \times ADT \times \%N\_ADT \times N/D \times DCR \times CRF \times ACC}{100{,}000{,}000 \times (AIC + AMC + AEC)}$$

where, the variables ADT, %N_ADT, N/D, DCR, CRF, ACC, AIC, AMC, and AEC are as defined in Table 6.

The installation was considered beneficial if the ratio is greater than 1.

Code	Variable	Unit
%N_ADT	Percentage of night-time traffic	% of average daily traffic
N/D	Night-to-day crash rate ratio	Ratio
DCR	Day crash rate	Crashes per 10 VMT
CRF	Crash reduction factor	% of current crashes
ACC	Average crash cost	$ per crash
AIC	Annualized installation cost of lighting	$ per year per mile
AMC	Annual maintenance cost	$ per year per mile
AEC	Annual energy cost	$ per year per mile

Table 6. Benefit to Cost Analysis Variables

Rea et al. (2009) defined the benefit to cost ratio as the ratio of reduced crash or societal costs as a result of decrease in the number and/or severity of crashes/crimes to the direct costs to the agency (initial installation, maintenance, and repair).

$$B/C\ Ratio_{j-i} = \frac{(SC_i - SC_j)}{(DC_j - DC_i)}$$

where,

B/C $Ratio_{j\text{-}i}$ = Incremental benefit to cost ratio of alternative j to alternative I,

SC_i and SC_j = Societal costs for alternatives i and j (annualized over the analysis period), and,

DC_i and DC_j = Direct costs for alternatives 1 and 2 (annualized over the analysis period).

The investment was considered beneficial over the analysis period if the ratio is greater than 1.

2.4. Lighting Cost, Privatization / Outsourcing and Payment Options

The cost of installation and maintenance of lighting on roadway network is enormous, often requiring a need for prioritization of locations that need lighting. Lambert and Turley (2003) estimated that the cost of a typical single high mast installation exceeds $100,000. Over $450,000 is required annually to maintain all conventional and high mast equipment (1,000 poles) in central Virginia. Their study also noted that $750,000 of electricity costs for lights and signals in the same region are needed annually. The study also looked at the cost of leasing and owning the lighting installations.

The discussion of whether or not to privatize public services usually begins when City and County governments have to do more with less money, due to rising costs and declining revenues (Machado, 2009). The different forms of privatization are outsourcing, design build operate (DBO), PPP and asset sale. The most common type of privatization is contracting out programs or services to a private firm. The contracting government is still responsible for the service even though the private firm provides the service. This is achieved through Request for Proposal (RFP) process or an Invitation to Bid (ITB). In the RFP process, any and all qualified private firms may submit a proposal to the government agency that describes in detail how they would perform the particular service and for what cost. It is not necessary that the private firm proposing to get the work done at the lowest cost wins the contract (Machado, 2009). Often times, a private firm demonstrating that they can provide the service to improve and operate more economically at the same time wins the contract. An ITB is the standard sealed competitive bid in which the lowest bidder usually gets the job (Machado, 2009).

The agencies most successful in privatization created a permanent, centralized entity to manage and oversee the operation, from project analysis and vendor selection to contracting and procurement. Outsourcing deals can turn into costly disasters for governments that forgo due diligence, choose ill-equipped contractors and fail to monitor progress (Nichols, 2010). A good outsourcing deal starts with a thorough benefit/cost analysis to see if a third party can effectively deliver services better and more cheaply than public employees (Nichols, 2010). The government agencies should complete an effective benefit/cost analysis prior to procurements. In addition to this, proper monitoring is required because policies will not work if departments do not participate.

Sachdev (2001) concluded that PPP has increased job insecurity in public sector. However, the workforce issues are highly controversial among PPPs. The private firms will deliver more work with less labor intensity and also by changing staff working practices. The savings of private sector are mainly derived at the expense of staff jobs, pay and conditions, particularly for the new recruits.

Wai (2006) conducted a study to analyze the effect of shopping center management outsourcing on service quality. A survey was conducted with a sample set of selected shopping centers. The results have revealed that there were significant differences of property management agents performance with respect to service quality level between Honk Kong Housing Authority (HKHA) and the Link Management Limited (the Link), a private sector entity. The survey indicated that the private firm delivers more value added services through better management practices and enhanced corporate competitiveness.

A survey of AASHTO members on roadway lighting was conducted by the AASHTO Joint Technical Committee on Roadway Lighting in December 2010. Thirty-six Departments of Transportation (DoTs) participated in the survey. The participants included 35 in the United States and 1 from Canada. Table 7 summarizes the details of ratio of design performed by the DoTs compared to consultants or others in lighting design from that study.

Project Cost ($)	% of DoTs by Response					
	A	B	C	D	E	F
< 50,000	29.4	11.8	23.5	14.7	14.7	5.9
50,000 - 250,000	20.0	28.6	14.5	14.3	20.0	2.9
250,000 - 500,000	16.7	22.2	8.3	13.9	27.8	11.1
> 500,000	11.4	22.9	0.0	8.6	40.0	17.1

Table 7. Ratio of Design Performed for Different Projects

In Table 7, response is defined as follows.

A 100% in-house

B 25% in-house and 75% consultant or other

C 50% in-house: 50% consultant or other

D 75% in-house and 25% consultant or other

E 100% consultant or other

F Information is not readily available

DiNapoli (2007) audited roadway lighting systems of five municipalities in the state of New York for years 2005 and 2006. The two classifications of audit are 1) owned and maintained by utility company, and, 2) owned by customer and maintained by utility company. The objective of the audit was to identify if the lighting costs could be reduced if municipalities acquire their lighting systems from their local electric utility companies. They compared the five municipalities which do not own their lighting systems (but are leasing the roadway lighting equipment from their local electric utilities) with the town of Union that purchased their roadway lighting system in 1998 and saved significant costs. The roadway lighting systems of the selected municipalities ranged from 1,115 to 2,638 roadway lights of varying wattages, type and styles of lights. The equipment leased included any combination of lamps, poles, cabling and conduit. Their analysis indicated a potential aggregate cost savings of over $13.1 million over the term of bonds (20 year) if municipalities acquired their roadway lighting systems (financed the purchase with 20-year bonds) and maintained them in-house.

Another option would be to lease the lighting system. As an example, the city of Wilmington, North Carolina leased 8,750 roadway lights from Progress Energy Carolinas (PEC). PEC installed and maintains the roadway lights in the city of Wilmington, NC. The monthly lease rate of each HPS roadway light is $9.51. However, no published documents discussing this option and its effectiveness for roadway lighting system could be found in the literature at the time of this research.

2.5. Modernization and New Lighting Technology Options

Adequate roadway lighting improves safety and appearance of the environment contributing to the quality of life. However, factors such as growing population, increasing maintenance and replacement costs, and increasing energy usage are magnifying the cost of roadway lighting to the local governments. According to a research by Culver & Kitira (2009), about 39 percent of the energy consumed in the United States is used to generate electricity. In 2007, electricity production consumed 36 percent of the fossil fuels used in the United States and generated 42 percent of fossil fuel-based CO2 emissions. With the limited resources available to provide appropriate roadway lighting, there is a need for implementing emerging technologies and creative ways to reduce the total cost on roadway lighting and energy consumed without altering the quality of life.

The most commonly used ranges of HPS or Mercury Vapor lamps for main roads are 250 W and 400 W units with occasional use of the 150 W lamps (Geoff and Poulton, 1999). The metal halide lamp has more than a 30% higher efficiency than the mercury vapor lamp and the use of this lamp would result in a 30% increase of light on the road surface and a reduction in energy consumption. Similarly, HPS lamps have 30% higher efficiency than metal halide lamps. As a result, most of the municipalities use HPS luminaires.

There seems to be growing trend toward the use of LED luminaries in recent years. Many pilot studies have been conducted to evaluate the benefits of replacing HPS luminaires with LED luminaires. According to Alpernas (2010), the feasibility and cost-effectiveness of LED implementation depends on the following factors.

- Cost and the return on investment.
- One-time initial investment in the new technology, including the acquisition of LED lights and retrofitting of the existing fixtures; might be too high for the city to absorb and the return on investment might not justify the initial expense.
- Public acceptance.
- Changes in roadway lighting patterns and the color and warmth of the new lights might cause resistance of the constituents and, consequently, a political backlash.

Narendran et al. (2007) conducted a study on long term performance of LED luminaires and found that the life of pc-white LED luminaires follow an exponential decay as a function of board temperature and has an increasing light output generation rate. Henderson (2009) discussed technical findings based on before-after analysis of LED fixtures. The study considered nine 167 W LED test fixtures that replaced two 200 W and seven 250 W HPS roadway light fixtures on the 100 block of East Davie Street in downtown Raleigh in October, 2008. Findings from Henderson's 2009 study include:

- 51% footcandle reduction measured at selected points along the study section with LED lighting;
- 8% footcandle reduction measured at selected points on the sidewalks with LED lighting;
- 43% footcandle reduction as calculated on the entire study section with LED lighting;
- 42% wattage reduction with LED lighting; and,
- uniformity (average to minimum) improved per calculations with LED lighting.

A study by Johnson et al. (2010) on replacing HPS luminaire with LED luminaire in a parking lot showed a great potential for energy savings. The results indicate that the costs and savings upon replacing HPS luminaire with LED luminaire provided favorable payback scenarios for both new construction and retrofit scenarios, due to significant maintenance and energy cost savings.

In another study (Kinzey et al., 2009), where eight HPS fixtures were replaced with LED fixtures in Oregon, it was found that LED fixtures result in an estimated payback of

7.6 years for new installations. The measured energy savings of 55% supporting the paybacks were achieved by reducing average illuminance levels by 53%. The output from the complete luminaire indicated that the LED luminaire does in fact produce only about half the light output (~3,000 lumens) as the traditional HPS cobra head (~6,700 lumens). The LED product was able to meet the applicable Portland lighting specification.

Mutmansky et al. (2010) conducted an assessment of advanced roadway lighting technologies at eight areas in the downtown San Diego. Existing lighting technologies were compared with more efficient broad spectrum lighting technologies to test their efficiency and sustainability. Existing HPS luminaries were compared against LED luminaires and Induction light sources using energy evaluations, subjective surveys and objective performance surveys. The study found a 40 percent energy savings, reduced GHG emissions, improved color rendering and reduced maintenance costs when broad spectrum (LED and Induction) lighting technologies were used.

Replacing the existing system with LED luminaires would help in reducing the energy usage, pollution and long-term costs (Alpernas, 2010). Cook et al. (2008b), through assessments conducted for Oakland, CA, found that the metered LED luminaire drew an average of 77.7 watts, roughly 35% (43.3 watts) less than the metered HPS luminaire. With an estimated 4,100 annual hours of operation, annual electrical savings are estimated to be approximately 178 kWh per luminaire replaced. LED luminaires also provide uniformity in lighting when compared to high luminance exactly on the area beneath the HPS lighting. Results also indicate a long payback period for the LED roadway light products used, which can be acceptable considering reduced energy utilization by over one-third compared to HPS luminaires.

Beckwith et al. (2011) assessed the potential benefits of installing LED luminaires instead of HPS luminaires in Seattle, Washington. Their research objective was to select the LED luminaire that could replace the presently installed 100 W HPS and 150 W HPS luminaires. Simulated photometric performance evaluation, field photometric performance evaluation and economic evaluation of various luminaires were conducted. A total of 10 LED luminaires from 3 different vendors varying in array size, color correlated temperature and amperage were considered. Luminaire A2: 60 W LED - Type

II Distribution – 4,300K - 525mA showed the best lighting performance with a 6.1-year payback on investment. A total of $43.36 of savings was calculated on annual operations and maintenance cost per luminaire when compared to 100 W HPS luminaires.

A study was conducted by United States Department of Energy, Pacific Gas & Electric, City of Oakland, CA, and Energy Solutions and Beta LED, Inc. on luminaires installed along Sextus Road, Cairo Road and Tunis Road in a residential area in the City of Oakland, CA (Cook et al., 2008b). Sextus Rd was illuminated with fresh HPS luminaires on the eastern half and LED luminaires on the western half, and Tunis Rd was illuminated exclusively with LED luminaires, while the adjacent Cairo Rd was entirely relamped with new HPS lamps. It was observed that LED luminaires consumed 35% less power compared to HPS luminaires. The LED luminaires maintained minimum light levels across all spacing while significantly improving uniformity ratios. A customer opinion survey conducted showed 17 out of the 20 respondents felt that the new luminaires were at least as preferable. The annual maintenance savings was estimated as a range from $0 per luminaire to $30 per luminaire and a payback period of 20 years.

Long et al. (2011) conducted a study to determine the feasibility of transitioning from standard HPS luminaire to LED luminaire on Missouri Department of Transportation (MoDOT) maintained roadway system. Their study included performance evaluations, a feasibility analysis and a potential replacement program. The performance of eight (Dialight, GE, Phillips, Holophane, Beta LEDway, American Electric, LED Roadway and Lighting Science Group) commercial LED luminaires was evaluated. The illuminance readings were compared to each luminaire's IES file to validate the manufacturer's claims. The IES files were analyzed using Visual's Roadway Lighting Tool. A total of 31 readings were collected for each luminaire. These readings included 15 readings at ground level and 15 readings elevated 18 inches above ground level in addition to one ambient reading collected in a non-illuminated area near the luminaire. These ambient readings were subtracted from the field readings to calculate adjusted field readings, which were then used to compare to each luminaire's IES file data. Four out of the nine luminaires were deemed acceptable to use for 30 foot mounting heights. The sensitivity analysis determined the variables with the greatest impact on the annualized cost of LED luminaires as price of the luminaire and the expected lifetime of the luminaire. Energy savings of 11% for 150 W equivalent luminaires was calculated. It was found that replacing one 150 W HPS lamp with the Dialight luminaire (evaluated LED luminaire) avoids the release of approximately 108 lbs of CO_2 into the atmosphere. LED roadway luminaires for most manufacturers meet existing spacing of previous HPS luminaire requirements.

Recently, roadway light bulbs on the 3rd Street of market area in the city of Wilmington, NC were replaced with LED luminaires. The height of LED luminaire post is 25 to 30 ft at intersections and 14 to 16 ft along the roadway. However, they were replaced with HPS luminaire as the people in the city were not satisfied with the brightness of light. This finding is contrary to what was observed in other LED luminaire evaluation studies.

Results from a survey conducted by AASHTO Joint Technical Committee on Roadway Lighting indicate that LED roadway lighting is used by 55.6% of DoTs. However, only 2 DoTs have specifications for LED lighting. Sign lighting is not practiced by most DoTs, while 61.8% DoTs are deactivating sign illumination. About 45% of DoTs have policy for designing roadway lighting at roundabouts.

2.6. Dimming and Trimming of Roadway Lights

The M65 was the first motorway to implement dimmable lighting in the United Kingdom (Collins et al., 2002). The strategy was implemented based on traffic flow to study energy consumption and safety. According to the strategy, the lighting level provided was 100% if vehicles per hour is greater than 3,000. The lighting level was reduced to 75% if vehicles per hour is 1,500-3,000, whereas it was reduced to 50% if vehicles per hour is less than 1,500. The results showed that the adaptive lighting dimming control provided many benefits. The reduction in energy consumption was 24% annually (decreased from 637,377 kWh to 484,581 kWh). The energy cost dropped from £26,769 (~$40,000) per year to £12,600 (~$19,000) when the controlled dimming is applied. CO_2 emissions fell from 274 tons to 129 tons. Further, results showed that the reduction in ocular stress most likely improved roadway safety by enabling motorists to remain more alert and reduce the risk of accidents.

The Highways Agency for the Department of Transport in England conducted a study of dimming roadway lighting and its effects on energy saving and maintenance costs (Metrolight, 2010). In 2008, the agency wanted to test this energy savings plan on the A1 Motorway in Northeast England. The existing situation was 250 W magnetic ballasts which were operating 12 hours a day. The plan that was implemented simply dimmed the 250 W lights to 200 W. This achieved an energy savings of 43%. Maintenance costs were reduced by 60% due to longer life of light bulb predicted. The annual CO2 savings were 2,607 metric tons and the total annual savings was £57,600 (~$87,000). A total of 900 units were replaced in three phases over one year and the payback period was found equal to 3.9 years.

Mutmansky and Garcia (2011) assessed six different advanced roadway lighting technologies on a test roadway in San Jose, CA. These different technologies were three different LED manufacturers, an induction lamp technology, HPS lamp, and the current low pressure sodium (LPS) lamp which are installed in vast majority in San Jose, CA. The project consisted of six test areas and each test area had a different light source technology and manufacturer. Also, each test area had eight roadway lamps. The analysis was done on two days. The first day the lamps were at full power, however on the second day, the lamps were dimmed to approximately 50 percent power except for the LPS lamps which were intentionally kept at full power. To conduct the analysis, two types of tests were conducted. One was a subjective survey where 55 participants were told to take a survey of 13 statements for each test area at night. The second type of test was an objective test where 36 people each night travelled in a specially equipped vehicle that performed a test for small target visibility. The test basically evaluated the participants' ability to detect small colored objects under different lighting conditions. The results from both the subjective survey and the objective test were mostly in favor of LED and induction technologies for light source. In terms of power consumption the maximum savings could be achieved with a 90 W LED which provided a 44% savings in full power mode and 73% savings in low power mode when compared to LPS lamps. It was estimated that, with adaptive controls, the energy consumption could be reduced 45%-64% annually. Their objective test results also showed that the mean detection distance generally drops on the low power light. However, it is mostly at the same level as the LPS on full power if not slightly lower.

CHAPTER 3. DIVISION LEVEL ASSESSMENT OF LIGHTING NEEDS AND ALLOCATION OF FUNDS

Providing roadway lighting to entire road network is practically not feasible due to the limited availability of transportation resources and extent of system needs. In North Carolina, the installation of a new lighting system along full access controlled facilities is considered as a part of a new roadway construction project if justified for lighting, with input from the Division. A separate funding is provided by the Lighting Committee for the new installation.

Resources are allocated at Division level for roadway lighting system maintenance and modernization of existing lighting systems. These resources are then prioritized and assigned for maintenance and modernization at specific locations. However, there is no widely accepted method or process currently available or adopted to assess maintenance and upgrade needs at NCDOT Division level and allocate funds for improved lighting system in North Carolina. This chapter presents two methods and results obtained from these methods for allocation of funds at division level in North Carolina.

3.1. Assessment of Division Level Needs

The state of North Carolina has 14 Divisions for allocation of maintenance funds based on the need. The Divisions comprise both urban and rural areas with notable variations in total population, the number of interchanges and freeway miles with and without lighting systems, access controlled facilities (center-lane miles), crash statistics, and night-time traffic volume. Table 8 shows population for the year 2010, the number of interchanges with lighting system, the number of interchanges without lighting system and the total number of interchanges of each Division. Table 9 shows center-lane miles of full access control, partial access control and total access control for Interstates, US Routes, NC Routes and secondary roads by Division in North Carolina. Table 10 shows night-time crashes, day-time crashes and total crashes during 2008, 2009 and 2010 by Division in North Carolina. The number of crashes on all facilities as well as crashes on full access controlled and partial access controlled facilities are summarized in the table. The computed night-to-day crash ratio based on the average number of crashes is also shown in the table for each Division.

The population is the highest for Division 5, followed by Divisions 10 and 7. It is the lowest for Division 1 followed by Division 14. The number of interchanges is the highest for Division 5 followed by Divisions 9, 10, 7 and 4. Division 10 has the highest number of interchanges with lighting, while Division 5 has the highest number of interchanges without lighting.

The average of total number of crashes for the 3 year period was observed to be the highest for Division 5, followed by Divisions 10 and 7. It was observed to be the lowest for Division 1. The average number of night-time and day-time crashes also followed the same trend. However, the computed night-to-day crash ratio was observed to be the highest for Division 1. It was observed to be relatively low for Divisions 5 and 10. On the other hand, the average number of night-time crashes, the average number of day-time crashes and the average number of total crashes on full access controlled and partial access controlled facilities for the 3 year period was observed to be the highest for Division 10 followed by Division 5. The night-to-day crash ratio based on crashes on full access controlled and partial access controlled facilities was observed to be the highest for Division 7. This indicates that using crashes on all facilities or night-to-day crash ratio for lighting assessments, prioritization or allocation of funds may not yield expected benefits. Night-to-day crash rate ratio could not be considered as traffic data were not available for all roads in each Division. Using the assumption that night-time traffic is 25% of total daily traffic in computing rates will not lead to any different allocation than what would be obtained based on night-to-day crash ratio.

A survey of Division level lighting needs was conducted by NCDOT staff during 2005, spring of 2011 and recently in early 2013. Data gathered was summarized to assess replacement / repair needs by type of lighting system (single arm, twin arm or high mast). Table 11 summarizes Divisions surveyed and number of lighting systems replaced, removed or repaired. Table 12 summarizes single arm, twin arm and high mast lighting systems replaced or not replaced in each division. Table 13 summarizes routes on which lighting systems were replaced while Table 14 summarizes routes on which lighting systems were not replaced. These summaries are based on spring 2011 survey of Division level lighting needs.

Division	Population (P_i) for the Year 2010	# Interchanges		
		With Lighting ($I_{i,L}$)	Without Lighting ($I_{i,WL}$)	Total ($I_{i,T}$)
1	264,551	0	35	35
2	490,035	0	35	33
3	662,023	8	50	58
4	579,818	10	92	102
5	1,394,973	38	118	156
6	661,565	9	51	60
7	890,700	42	71	113
8	508,916	4	84	87
9	740,617	25	92	117
10	1,386,464	50	63	113
11	371,760	1	61	62
12	733,422	9	76	85
13	496,197	18	58	76
14	275,958	1	38	38
Total	9,456,999	215	924	1,135

Table 8. Population and Approximate Numbers of Interchanges by Division

Division	Center-lane Miles												
	Interstate			US Route			NC Route			Secondary Route			Total
	Full Access Control	Partial Access Control	Total	Full Access Control	Partial Access Control	Total	Full Access Control	Partial Access Control	Total	Full Access Control	Partial Access Control	Total	
1	8	0	8	69	38	107	0	7	7	0	2	2	124
2	0	0	0	55	53	108	3	14	17	0	0	0	125
3	87	0	87	31	63	94	4	9	13	0	2	2	196
4	151	0	151	103	47	150	1	2	3	2	1	3	307
5	145	0	145	62	22	84	20	2	22	3	8	11	262
6	102	9	111	24	42	66	6	19	25	11	6	17	219
7	123	4	127	38	43	81	0	4	4	9	14	23	235
8	69	1	70	85	72	157	0	3	3	5	6	11	241
9	107	14	121	62	2	64	0	22	22	1	45	46	253
10	130	0	130	3	14	17	1	24	25	2	10	12	184
11	49	0	49	48	28	76	0	5	5	0	1	1	131
12	109	0	109	42	13	55	8	6	14	2	4	6	184
13	115	0	115	36	20	56	0	0	0	0	1	1	172
14	67	0	67	42	12	54	0	8	8	0	2	2	131
Total	1,262	28	1,290	700	469	1,169	43	125	168	35	102	137	2,764

Table 9. Access Control Facilities by Functional Class and Division

Division	# Night-time Crashes ($C_{i,N}$)				# Day-time Crashes ($C_{i,D}$)				# Total Crashes ($C_{i,T}$)				Night-to-day Crash Ratio
	2008	2009	2010	Average	2008	2009	2010	Average	2008	2009	2010	Average	
Crashes on All Facilities													
1	2,143	2,271	2,296	2,237	2,861	3,104	3,101	3,022	5,004	5,375	5,397	5,259	0.74
2	3,857	3,881	4,152	3,963	6,764	6,603	7,145	6,837	10,621	10,484	11,297	10,801	0.58
3	5,621	5,660	5,716	5,666	9,124	9,090	9,851	9,355	14,745	14,750	15,567	15,021	0.61
4	4,867	4,960	4,867	4,898	7,685	8,109	8,192	7,995	12,552	13,069	13,059	12,893	0.61
5	10,677	10,700	10,637	10,671	23,564	23,382	24,081	23,676	34,241	34,082	34,718	34,347	0.45
6	5,552	5,485	5,566	5,534	10,190	10,497	10,696	10,461	15,742	15,982	16,262	15,995	0.53
7	6,901	7,031	6,753	6,895	12,904	13,065	13,206	13,058	19,805	20,096	19,959	19,953	0.53
8	3,894	3,776	3,997	3,889	6,500	6,438	6,561	6,500	10,394	10,214	10,558	10,389	0.60
9	5,207	5,199	4,974	5,127	10,605	10,759	10,585	10,650	15,812	15,958	15,559	15,776	0.48
10	10,222	9,179	9,139	9,513	25,338	21,138	21,926	22,801	35,560	30,317	31,065	32,314	0.42
11	2,664	2,532	2,494	2,563	5,247	5,235	5,333	5,272	7,911	7,767	7,827	7,835	0.49
12	5,082	4,773	4,842	4,899	11,109	10,985	10,998	11,031	16,191	15,758	15,840	15,930	0.44
13	2,701	2,709	2,801	2,737	6,536	6,706	7,466	6,903	9,237	9,415	10,267	9,640	0.40
14	1,809	1,810	1,615	1,745	4,734	4,618	4,583	4,645	6,543	6,428	6,198	6,390	0.38
Crashes on Full and Partial Control Access Facilities													
1	148	192	232	191	470	450	456	459	618	642	688	649	0.42
2	254	287	337	293	679	565	627	624	933	852	964	916	0.47
3	574	667	682	641	1,109	1,307	1,409	1,275	1,683	1,974	2,091	1,916	0.50
4	1,030	1,074	1,201	1,102	2,071	2,297	2,303	2,224	3,101	3,371	3,504	3,325	0.50
5	3,034	3,001	3,176	3,070	7,704	7,355	7,859	7,639	10,738	10,356	11,035	10,710	0.40
6	1,087	1,123	1,084	1,098	2,840	2,619	2,711	2,723	3,927	3,742	3,795	3,821	0.40
7	1,462	1,588	1,478	1,509	2,823	2,932	2,861	2,872	4,285	4,520	4,339	4,381	0.53
8	528	494	542	521	1,341	1,340	1,437	1,373	1,869	1,834	1,979	1,894	0.38
9	1,432	1,625	1,584	1,547	3,735	4,071	3,974	3,927	5,167	5,696	5,558	5,474	0.39
10	3,295	3,140	3,182	3,206	9,189	7,987	8,275	8,484	12,484	11,127	11,457	11,689	0.38
11	352	356	404	371	896	945	838	893	1,248	1,301	1,242	1,264	0.42
12	950	1,026	1,073	1,016	2,328	2,266	2,297	2,297	3,278	3,292	3,370	3,313	0.44
13	896	963	1,093	984	2,599	2,836	3,424	2,953	3,495	3,799	4,517	3,937	0.33
14	535	547	461	514	1,592	1,547	1,412	1,517	2,127	2,094	1,873	2,031	0.34

Table 10. Night-time and Day-time Crashes by Division

Division	Interchange Lighting, Roadway Lighting, Area Lighting or Sign Lighting	
	Total Surveyed	Repaired, Replaced or Removed
1	2	2
2	7	3
3	5	5
4	30	5
5	NA	NA
6	3	3
7	2	2
8	NA	NA
9	9	9
10	3	3
11	4	4
12	14	14
13	5	5
14	38	28
Total	122	83

Table 11. Spring 2011 Survey Summary

Divison	Replaced				Not Replaced			
	Single Arm	Twin Arm	High Mast	Total	Single Arm	Twin Arm	High Mast	Total
1	NA	NA	NA	NA	NA	NA	NA	NA
2	NA	NA	NA	NA	NA	NA	NA	NA
3	2	0	4	6	123	2	2	127
4	33	0	3	36	217	10	36	263
5	0	0	0	0	292	192	95	579
6	0	0	0	0	69	31	12	112
7	178	18	12	208	589	417	108	1,114
8	NA	NA	NA	NA	NA	NA	NA	NA
9	0	0	0	0	330	0	26	356
10	520	27	28	575	919	377	159	1,455
11	0	0	0	0	28	4	2	34
12	18	0	48	66	0	0	55	55
13	148	0	2	150	554	82	55	691
14	NA	NA	NA	NA	NA	NA	NA	NA
Total	686	27	78	791	1,831	463	297	2,591

Table 12. Interchange Lighting Systems Replaced or Not Replaced by Division from Spring 2011 Survey

Route	Total Street Lights Replaced			
	Single Arm	Twin Arm	High Mast	Total
I-277	114	0	0	114
I-277 / S. Caldwell St.	16	6	3	25
I-40	93	0	46	139
I-40 & I-77	0	0	2	2
I-40 / US-29	6	0	6	12
I-77	322	21	15	358
I-85	68	18	10	96
I-85 / I-40	45	0	6	51
I-95	33	0	3	36
NC-191	33	0	2	35
NC-68	14	0	0	14
US-17 / SR-1472	2	0	4	6
US-19; US-23	40	0	0	40
US-29	113	0	0	113
Total	899	45	97	1,041

Table 13. Interchange Lighting Systems Replaced by Route from Spring 2011 Survey

Route	Total Street Lights Not Replaced			
	Single Arm	Twin Arm	High Mast	Total
BYP US-19/23	23	0	2	25
Greensboro Western Loop	18	12	2	32
I-240	142	10	10	162
I-240 / US-74/70	70	39	0	109
I-26	17	0	4	21
I-277	27	0	0	27
I-277 / Caldwell St.	10	5	3	18
I-277 / NC-16 & 7th St.	8	0	3	11
I-277 / NC-16 & Caldwell St.	35	0	0	35
I-277 / NC-16 & Graham St.	25	0	0	25
I-40	221	196	127	544
I-40 & I-77	0	0	2	2
I-40 Bus / US-421	60	0	5	65
I-40 Bus / US-421/158	97	0	0	97
I-40 / I-85	15	0	3	18
I-40 / Stratford Rd	23	0	0	23
I440 / Wake Forest Rd	4	0	0	4
I-485	6	0	8	14
I-540	70	15	19	104
I-77	429	80	95	604
I-77 & US-421	28	4	2	34
I-77 / I-277	13	0	3	16
I-85	638	623	129	1,390
I-85 & I-40	8	10	4	22
I-85 / I-40	55	4	11	70
I-85 / US-52	24	0	2	26
I-95	215	41	42	298
I-95 & NC-50	20	0	2	22
I-95 & NC-53	31	0	2	33
I-95 & US-158	20	0	2	22
Lewisville-Clemmons Rd / US-421	19	0	2	21
Loop	29	17	2	48
NA	0	0	3	3
NC-146	0	0	3	3
NC-191	8	6	4	18
NC-191 Conn.	30	0	0	30
NC-191 / I-40	24	0	0	24
NC-68	28	0	2	30
NC-17	29	2	2	33
NC-191 / I-26	33	0	2	35
NC-8 / I-85	0	0	3	3
Smith Creek Parkway	37	0	0	37
SR-3548	9	0	0	9
US 15-501	0	0	4	4
US-19/23	68	0	0	68
US-220 BUS	5	0	0	5
US-23 (I-23)	25	0	0	25
US-23(I-23)	7	0	0	7
US-29	22	0	2	24
US-29 (O'Henry Blvd)	47	0	6	53
US-29A; US 70A	15	0	3	18
US-29; US 70	8	0	6	14
US-311	0	0	2	2
US-70	21	0	0	21
US-74	245	22	10	277
US-1	0	0	2	2
US-1 / US-64	0	15	4	19
US-1; US-64	3	14	6	23
US-421	57	0	0	57
Total	3,121	1,115	550	4,786

Table 14. Interchange Lighting Systems Not Replaced by Route from Spring 2011 Survey

3.2. Methodology to Assess and Allocate Funds for Lighting System Maintenance and Modernization at Division Level

Divisions 5 and 10 comprise major urban areas with higher population, heavily traveled freeways and hence higher night-time activity and traffic volume. The frequency of crashes tends to be higher in these Divisions due to an increase in exposure. Considering these factors for allocation will help cater the needs of many drivers and maximize derived benefits.

Funds should be allocated for the maintenance and modernization of existing lighting systems. Therefore, the number of interchanges with lighting in a Division is an important parameter for consideration and allocation of funds. On the other hand, fatal crashes and night-time crashes are high in Divisions (example, Division 1 with high night-to-day crash ratio) with rural areas. Providing improved lighting systems at interchanges in such Divisions could enhance night-time safety.

The focus, hence, is to devise a methodology that would help assess the maintenance needs by taking the above identified factors into consideration and efficiently allocating funds to Divisions in North Carolina. Two different methods are proposed to assess the maintenance / upgrade needs and allocate funds. The first method takes population, the number of interchanges with lighting systems, and the number of night-time crashes on full access controlled and partial access controlled facilities within the Division into consideration, while the second method takes population, the number of interchanges with lighting systems and the total number of crashes on full access controlled and partial access controlled facilities within the Division into consideration. Percentages related to each factor are computed and summed to attain a final score. The final scores computed for all Divisions are then used to assess relative need for funds for each Division. The percent of funds to be allocated to each Division are then computed based on this relative need (score). Both the proposed methods and results obtained are discussed next.

3.2.1. Method 1 Based on Night-time Crashes

As stated previously, method 1 takes population, the number of interchanges with lighting systems, and the number of night-time crashes on full access controlled and partial access controlled facilities within the Division into consideration.

Population

Traffic volume is a measure related to population. A higher population would be expected to correspond to higher night-time activity and travel. It is also an indicator of the number of people that would be benefited due to enhanced lighting systems. This factor was hence taken into account for assessment of lighting needs and allocation of maintenance / upgrade funds at Division level.

Demographic data from the Census Bureau website, for the year 2010, was used to summarize the total population of each Division. The percent population of a Division was computed by dividing the population of that Division with the total population of North Carolina and then multiplied by 100.

Number of Interchanges with Lighting Systems

The number of interchanges with lighting systems is an indicator of existing possible annual maintenance costs and related needs. This factor was hence taken into account for assessment of lighting needs and allocation of maintenance / upgrade funds at the Division level.

The recent data (spring 2013) pertaining to the approximate number of interchanges with lighting systems was gathered from NCDOT staff (collected from Division level staff surveys). This information was verified using Google Maps and selected field visits. The percent of interchanges with lighting systems in a Division was computed by dividing the number of interchanges with lighting systems of that Division with the total number of interchanges with lighting systems in North Carolina and then multiplied by 100.

Night-time Crashes

The lack of suitable lighting systems at interchanges could increase potential risk to transportation system users, reduce navigation capabilities and result in night-time crashes and. As lighting systems primarily assist drivers during night-time, the night-time crashes along full access controlled and partial access controlled facilities was taken into account for assessment of lighting needs and allocation of maintenance / upgrade funds at the Division level.

The number of night-time crashes along full access controlled and partial access controlled facilities during years 2008, 2009 and 2010 were identified from NCDOT Crash Facts report. The average number of night-time crashes for the three-year period was computed. The night-time crash percent for a Division was then computed by dividing the average number of night-time crashes along full access controlled and partial access controlled facilities of that Division with the total number of night-time crashes along full access controlled and partial access controlled facilities in North Carolina and then multiplied by 100.

Combined Score 1

The computed percentages for population, interchanges with lighting systems and night-time crashes along full access controlled and partial access controlled facilities are summed to obtain the combined score based on method 1 for each Division. This is mathematically represented as:

Combined score based on method 1 for Division "i", $CS_{i,1}$

$$= (\% \text{ of } P_i) + (\% \text{ of } I_{i,L}) + (\% \text{ of } C_{i,N})$$

where, P_i is population, $I_{i,L}$ is interchanges with lighting systems and $C_{i,N}$ is night-time crashes along full access controlled and partial access controlled facilities for Division "i".

The combined score for a Division is an indicator of relative lighting needs for that Division. The sum of combined score for all Divisions is equal to 300 as three different factors are used. The percent of funds that need to be allocated to a Division using method 1 was finally computed by dividing the combined score based on method 1 for that Division with 300 and then multiplied by 100. This is mathematically represented as:

% funds allocated for Division “i” using method 1 = $(CS_{i,1}/300) * 100$

The Divisions were then ranked based on the computed combined score 1.

3.2.2. Method 2 Based on Total Crashes

As stated previously, method 2 takes population, the number of interchanges with lighting systems and the number of total crashes on full access controlled and partial access controlled facilities within the Division into consideration. The percentages for population and interchanges with lighting systems are computed as was discussed in case of method 1.

Total Crash Score

Roadway lighting also enhances visibility during adverse weather conditions. As the night-time crashes does not take into account the crashes during inclement weather conditions, the total crashes along full access controlled and partial access controlled facilities was taken into account for assessment of lighting needs and allocation of maintenance / upgrade funds at Division level. Considering the total crashes also helps account for general risk to drivers along the corridor.

The number of total crashes along full access controlled and partial access controlled facilities during years 2008, 2009 and 2010 were identified from NCDOT Crash Facts report. The average number of total crashes for the three-year period was computed. The total crash percent for a Division was then computed by dividing the average number of total crashes along full access controlled and partial access controlled facilities of that Division with the total number of crashes along full access controlled and partial access controlled facilities in North Carolina and then multiplied by 100.

Combined Score 2

The computed percentages for population, interchanges with lighting systems and total crashes along full access controlled and partial access controlled facilities are summed to obtain the combined score based on method 2 for each Division. This is mathematically represented as:

Combined score based on method 2 for Division "i", $CS_{i,2}$

$$= (\% \text{ of } P_i) + (\% \text{ of } I_{i,L}) + (\% \text{ of } C_{i,T})$$

where, P_i is population, $I_{i,L}$ is interchanges with lighting systems and $C_{i,T}$ is total crashes along full access controlled and partial access controlled facilities for Division "i".

The combined score for a Division is an indicator of relative lighting needs for that Division. As in the previous case, the sum of the combined score for all Divisions is equal to 300, as three different factors are used. The percentage of funds that need to be allocated to a Division using method 2 was finally computed by dividing the combined score based on method 2 for that Division with 300 and then multiplied by 100. This is mathematically represented as:

$$\% \text{ funds allocated to Division "i" using method 2} = (CS_{i,2}/300) * 100$$

The Divisions were then ranked based on the computed combined score 2.

3.3. Results Based on Evaluation of Methods for Allocation of Funds

Tables 15 and 16 show the assessment of maintenance / upgrade needs and allocation of funds using method 1 (night-time crashes) and method 2 (total crashes), respectively. No funds are allocated for lighting maintenance needs to Divisions 1 and 2 as they do not have any lighting systems ($\%I_{i,L} = 0$). Based on method 1, 20.02% of total available maintenance / upgrade funds are to be allocated to Division 10, followed by 17.83% of funds to Division 5. On the other hand, 20.42% of total available maintenance / upgrade funds are to be allocated to Division 10 based on method 2, followed by 17.91% of funds to Division 5. These two Divisions are followed by Division 7 using both the methods.

There are marginal differences in funds allocated to the Divisions based on the two methods. As roadway lighting systems are more meant for night-time travel, method 1 based on night-time crashes along full access controlled and partial access controlled facilities is recommended for use rather than method 2 based on total crashes along full access controlled and partial access controlled facilities.

Division	Population (P_i) for the Year 2010	# Interchanges			# Crashes	% P_i	% $I_{i,L}$	% $C_{i,N}$	Combined Score 1	% Allocation 1	Rank
		With Lighting ($I_{i,L}$)	Without Lighting ($I_{i,WL}$)	Total ($I_{i,T}$)	Night-time ($C_{i,N}$)						
1	264,551	0	35	35	191	2.8	0.0	1.2	0.00	0.00	13
2	490,035	0	35	33	293	5.2	0.0	1.8	0.00	0.00	13
3	662,023	8	50	58	641	7.0	3.7	4.0	14.71	5.09	9
4	579,818	10	92	102	1,102	6.1	4.7	6.9	17.64	6.10	8
5	1,394,973	38	118	156	3,070	14.8	17.7	19.1	51.54	17.83	2
6	661,565	9	51	60	1,098	7.0	4.2	6.8	18.02	6.23	7
7	890,700	42	71	113	1,509	9.4	19.5	9.4	38.35	13.27	3
8	508,916	4	84	87	521	5.4	1.9	3.2	10.49	3.63	10
9	740,617	25	92	117	1,547	7.8	11.6	9.6	29.09	10.07	4
10	1,386,464	50	63	113	3,206	14.7	23.3	20.0	57.87	20.02	1
11	371,760	1	61	62	371	3.9	0.5	2.3	6.70	2.32	11
12	733,422	9	76	85	1,016	7.8	4.2	6.3	18.27	6.32	6
13	496,197	18	58	76	984	5.2	8.4	6.1	19.74	6.83	5
14	275,958	1	38	38	514	2.9	0.5	3.2	6.59	2.28	12
Total	9,456,999	215	924	1,135	16,063	100	100	100	289.01	100.00	

Table 15. Division Level Assessment and Allocation of Funds using Method 1

Division	Population (P_i) for the Year 2010	# Interchanges			# Crashes	% P_i	% $I_{i,L}$	% $C_{i,T}$	Combined Score 2	% Allocation 2	Rank
		With Lighting ($I_{i,L}$)	Without Lighting ($I_{i,WL}$)	Total ($I_{i,T}$)	Total ($C_{i,T}$)						
1	264,551	0	35	35	649	2.8	0.0	1.2	0.00	0.00	13
2	490,035	0	35	33	916	5.2	0.0	1.7	0.00	0.00	13
3	662,023	8	50	58	1,916	7.0	3.7	3.5	14.18	4.90	9
4	579,818	10	92	102	3,325	6.1	4.7	6.0	16.79	5.81	8
5	1,394,973	38	118	156	10,710	14.8	17.7	19.4	51.78	17.91	2
6	661,565	9	51	60	3,821	7.0	4.2	6.9	18.09	6.26	6
7	890,700	42	71	113	4,381	9.4	19.5	7.9	36.87	12.75	3
8	508,916	4	84	87	1,894	5.4	1.9	3.4	10.67	3.69	10
9	740,617	25	92	117	5,474	7.8	11.6	9.9	29.35	10.15	4
10	1,386,464	50	63	113	11,689	14.7	23.3	21.1	59.05	20.42	1
11	371,760	1	61	62	1,264	3.9	0.5	2.3	6.68	2.31	12
12	733,422	9	76	85	3,313	7.8	4.2	6.0	17.93	6.20	7
13	496,197	18	58	76	3,937	5.2	8.4	7.1	20.74	7.17	5
14	275,958	1	38	38	2,031	2.9	0.5	3.7	7.06	2.44	11
Total	9,456,999	215	924	1,135	55,322	100	100	100	289.19	100.00	

Table 16. Division Level Assessment and Allocation of Funds using Method 2

CHAPTER 4. HIGH PRESSURE SODIUM (HPS) LUMINAIRE OR LIGHT EMITTING DIODE (LED) LUMINAIRE FOR ROADWAY LIGHTING - ECONOMIC ANALYSIS

An economic analysis comparing HPS luminaires to LED luminaires is presented in this chapter.

NCDOT currently uses 400 W HPS luminaires for single arm and twin arm street lighting systems at interchanges. These luminaires emit about 125 lumens per watt of light with an expected working life of 3 years. NCDOT also uses 250 W HPS luminaires at other facilities on roads while 400 W, 750 W and 1000 W HPS luminaires are used for high mast installations. The 250 W HPS luminaires emit about 114 lumens per watt of light with an expected working life of 3 years.

Based on an analysis and pilot study, the City of Los Angeles, CA (Unknown Year) found that replacement for 100 W, 150 W, 200 W, 310 W and 400 W HPS luminaires should use less than 73 W, 115 W, 145 W, 225 W and 280 W LED luminaires, respectively to achieve the desired energy savings. Howard Lighting Products (Unknown Year) present standard luminaires to LED wattage cross-reference. From their table, a 295 W HPS luminaire (250 W HPS and 45 W ballast loss) has lamp mean lumens of 27,000 and visually effective lumens of 11,718 while a 464 W HPS luminaire (400 W HPS and 64 W ballast loss) has lamp mean lumens of 45,000 and visually effective lumens of 19,530. In comparison, a 103 W LED luminaire has visually effective lumens of 11,726 and a 172 W LED luminaire has visually effective lumens of 19,582. These LED luminaires result in approximately 65% energy savings.

Beta LED (2008) present photopic and scotopic comparison charts pertaining to standard luminaires currently used for lighting (includes HPS) and LED luminaires. They indicate that a 300 W HPS luminaire (250 W HPS and 50 W ballast loss) has an initial delivered lumens of 13,020 and an average delivered lumens of 11,780 while a 460 W HPS luminaire (400 W HPS and 60 W ballast loss) has an initial delivered lumens of 21,700 lumens and an average delivered lumens of 19,840. In comparison, a 104 W LED luminaire (with 4 light bars) has initial delivered lumens of 13,328 and an average delivered lumens of 12,662 while a 153 W LED luminaire (with 6 light bars) has initial delivered lumens of 19,992 and an average delivered lumens of 18,992. Different manufacturers use different sized light bars, so while factually accurate for BetaLED the above does not provide a true point of reference for all LED luminaires.

Information obtained from PEC (Progress Energy, 2011) indicates that a 215 W LED luminaire emits about 65 lumens per watt of light with an expected working life of 12 years. On the other hand, a 105 W LED luminaire emits about 70.9 lumens per watt of light with an expected working life of 12 years.

Overall, information obtained online from various LED lighting manufacturer websites indicates that a ~250 W HPS luminaire could be effectively replaced by a ~105 W LED luminaire while a ~400 W HPS luminaire could be effectively replaced by a ~215 W LED luminaire. However, these findings have to be supported by economic analysis to determine the monetary benefits before testing or large-scale implementation.

While 105 W LED and 215 W LED are suitable for replacement, a 75 W LED was also considered to compare the monetary benefit of using a low wattage LED to a high wattage LED should adequate lighting standard levels be met, and also to understand possible trends in benefits with increase in wattage.

A summary of the characteristics of selected HPS and LED luminaires that were considered for economic analysis are shown in Table 17.

Luminaire Type	Watts	Quantity	Average Lighting Time (Hrs/Day)	Annual Energy Consumption (kWh)	Working Life (Years)
HPS	250	1	11	1,004	3
HPS	400	1	11	1,606	3
LED	75	1	11	301	12
LED	105	1	11	422	12
LED	215	1	11	863	12

Table 17. Characteristics of Selected HPS and LED Luminaires

As the average life of a HPS luminaire is 3 years (36 months) and the average life of a LED luminaire is 12 years (144 months), twelve years was used as the life of the interchange lighting project. HPS luminaires are installed and relamped thrice (at the end of years 3, 6 and 9) over the life of the project whereas LED luminaires are installed once at the beginning of the project.

Cost estimates to install or furnish and replace 250 W and 400 W HPS luminaires was obtained from NCDOT. Quotes pertaining to the installation or furnishing and replacing of LED lamps (75 W, 105 W and 215 W) was obtained from PEC. A 4% interest rate was used to compute net present values and conduct economic analysis.

The cost of replacing pole / fixture, personnel costs involved to replace or maintain pole, fixture or lamp, traffic control and management, and, delay cost due to disruption to traffic were ignored in the analysis. In other words, existing poles, mast arms and other fixtures were assumed suitable to replace HPS luminaires with LED luminaires. Further, the unit cost of HPS luminaire and LED luminaire were assumed to remain constant (though could generally decrease) over time.

4.1. Economic Analysis - Comparison of 250 W HPS and LED Luminaires

An economic analysis comparing 250 W HPS luminaires with 75 W, 105 W and 215 W LED luminaires is presented in this section.

The unit relamping cost of a 250 W HPS luminaire is around $152.40 whereas the unit relamping cost of 75 W, 105 W and 215 W LED luminaires are around $350.00, $400.00 and $750.00, respectively. The unit relamping cost for 250 W HPS luminaire at the beginning of the project and at the end of years 3, 6, and 9 are converted to their present value using an interest rate equal to 4% while the unit relamping lamp cost for LED luminaires at the beginning of the project was used as its present value.

The computed energy consumption of 250 W HPS luminaire is 1,003.75 kWh whereas the computed energy consumption of 75 W, 105 W and 215 W LED luminaires are 301.13 kWh, 421.58 kWh and 863.23 kWh, respectively. The energy consumed by the respective luminaires are converted into dollar value using $0.10 per kWh of energy consumed (current estimated unit energy cost in North Carolina). The energy consumption costs are then converted to their present value for each luminaire using an interest rate equal to 4%.

The total present value (relamping costs and energy consumption cost) are computed for each luminaire. The ratios of total present value are then computed for each LED luminaire by dividing the total present value for the LED luminaire with the total present value for 250 W HPS luminaire.

Table 18 shows furnishing & replacing light lamp cost, energy consumption cost per annum and total present value for 250 W HPS, 75 W LED, 105 W LED, and 215 W LED luminaires. The ratio of total present values for 75 W LED, 105 W LED, and 215 W LED luminaires to 250 W HPS luminaire are also shown in the table.

The total present value of 250 W HPS luminaire is $1,457.43, greater than 75 W and 105 W LED luminaires considered for analysis. The total present value of LED luminaires was observed to increase as the wattage increases. The ratio of total present value is lowest for 75 W LED luminaire (1:2.3) and highest for 105 W LED luminaire (1:1.8). The ratio of total present value was observed to increase with wattage. This indicates that benefits would be largest if a HPS luminaire can be replaced with the lowest wattage feasible / suitable LED luminaire. In this case, replacing a 250 W HPS luminaire with a 105 W LED luminaire would result in reduced costs but replacing a 250 W HPS luminaire with a 215 W LED luminaire would not result in reduced lamp and energy consumption costs.

Cost Category	Quantity	Cost	Total Cost
250 W HPS			
250 W HPS lamp	1	$152.40	$152.40
Energy consumption cost (Kwh) per annum	1,003.75	$0.10	$100.38
Total present value of 250 W HPS luminaire			$1,457.43
75 W LED			
75 W LED lamp	1	$350.00	$350.00
Energy consumption cost (Kwh) per annum	301.13	$0.10	$30.11
Total present value of 75 W LED luminaire			$632.61
Ratio of total present value (75 W LED to 250 W HPS)			1:2.3
105 W LED			
105 W LED lamp	1	$400.00	$400.00
Energy consumption cost (Kwh) per annum	421.58	$0.10	$42.16
Total present value of 105 W LED luminaire			$795.65
Ratio of total present value (105 W LED to 250 W HPS)			1:1.8
215 W LED			
215 W LED lamp	1	$750.00	$750.00
Energy consumption cost (Kwh) per annum	863.23	$0.10	$86.32
Total present value of 215 W LED luminaire			$1,560.14
Ratio of total present value (215 W LED to 250 W HPS)			1.1:1

Table 18. Economic Analysis – 250 W HPS Compared to LED Luminaires

4.2. Economic Analysis - Comparison of 400 W HPS and LED Luminaires

An economic analysis comparing 400 W HPS luminaires with 75 W, 105 W and 215 W LED luminaires is presented in this section.

The unit relamping cost of a 400 W HPS luminaire is around $177.80 whereas the unit relamping cost of 75 W, 105 W and 215 W LED luminaires are around $350.00, $400.00 and $750.00, respectively. The unit relamping cost for 400 W HPS luminaire at the beginning of the project and at the end of years 3, 6, and 9 are converted to their present value using an interest rate equal to 4% while the unit relamping cost for LED luminaires at the beginning of the project was used as its present value.

The computed energy consumption of 400 W HPS luminaire is 1,606.00 kWh whereas the computed energy consumption of 75 W, 105 W and 215 W LED luminaires are 301.13 kWh, 421.58 kWh and 863.23 kWh, respectively. The energy consumed by the respective luminaires are converted into dollar value using $0.10 per kWh of energy consumed (current estimated unit energy cost in North Carolina). The energy consumption costs are then converted to their present value for each luminaire using an interest rate equal to 4%.

The total present value (relamping costs and energy consumption cost) are computed for each luminaire. The ratios of total present value are then computed for each LED luminaire by dividing the total present value for the LED luminaire with the total present value for 400 W HPS luminaire.

Table 19 shows furnishing & replacing light lamp cost, energy consumption cost per annum and total present value for 400 W HPS, 75 W LED, 105 W LED, and 215 W LED luminaires. The ratio of total present values for 75 W LED, 105 W LED, and 215 W LED luminaires to 400 W HPS luminaire are also shown in the table.

The total present value of 400 W HPS luminaire is $2,108.54, greater than all LED luminaires considered for analysis. The total present value of LED luminaires was observed to increase as the wattage increases. The ratio of total present value is lowest for 75 W LED luminaire (1:3.3) and highest for 215 W LED luminaire (1:1.4). It was observed to increase with wattage. This indicates that benefits would be largest if a HPS luminaire can be replaced with the lowest wattage feasible / suitable LED luminaire.

A 75 W or 105 W LED luminaire is not a feasible replacement for a 400 W HPS luminaire. However, in this case, replacing a 400 W HPS luminaire even with a 215 W LED luminaire would still result in reduced costs.

Cost category	Quantity	Cost	Total Cost
400 W HPS			
400 W HPS Lamp	1	$177.80	$177.80
Energy consumption cost (Kwh) per annum	1,606.00	$0.10	$160.60
Total present value of 400 W HPS luminaire			$2,108.54
75 W LED			
75 W LED Lamp	1	$350.00	$350.00
Energy consumption cost (Kwh) per annum	301.13	$0.10	$30.11
Total present value of 75 W LED luminaire			$632.61
Ratio of total present value (75 W LED to 400 W HPS)			1:3.3
105 W LED			
105 W LED Lamp	1	$400.00	$400.00
Energy consumption cost (Kwh) per annum	421.58	$0.10	$42.16
Total present value of 105 W LED luminaire			$795.65
Ratio of total present value (105 W LED to 400 W HPS)			1:2.7
215 W LED			
215 W LED Lamp	1	$750.00	$750.00
Energy consumption cost (Kwh) per annum	863.23	$0.10	$86.32
Total present value of 215 W LED luminaire			$1,560.14
Ratio of total present value (215 W LED to 400 W HPS)			1:1.4

Table 19. Economic Analysis – 400 W HPS Compared to LED Luminaires

4.3. HPS or LED - Summary

Table 20 provides the difference in total present value (HPS luminaire minus LED luminaire) and ratio of total present value (LED luminaire to HPS luminaire) between HPS and LED luminaires considered in this research. The results obtained, in general, indicate that LED luminaires will reduce costs and yield monetary benefits. The difference in total present value and ratio of total present value, however, decreases as wattage of LED increases. In general, a 250 W HPS luminaire can be replaced with up to a maximum of 105 W LED luminaire, while a 400 W HPS luminaire can be replaced with even a 215 W LED luminaire. This indicates that larger benefits can be achieved by replacing higher wattage HPS luminaires with LED luminaires than compared to lower wattage HPS luminaires.

As stated previously, personnel costs involved to replace or maintain pole, fixture or lamp, traffic control and management, and delay cost due to disruption to traffic were ignored in the analysis. Considering these costs would increase cost of HPS luminaires (which require relamping these luminaires three times during a 12-year period compared to none for LED luminaires) and make it less economically feasible.

The DOE estimates that the cost of LED luminaire has dropped more than 25% in the past year (Peters, 2012). They are expected to further decrease while energy consumption costs are expected to increase in the future. The use of LED luminaires therefore will result in increased energy savings and make it even more cost-effective in the future.

Difference in Total Present Value		
	250 W HPS	**400 W HPS**
75 W LED	$824.82	$1,475.94
105 W LED	$661.78	$1,312.89
215 W LED	-$102.72	$548.40
Ratio of Total Present Value		
75 W LED	1:2.3	1:3.3
105 W LED	1:1.8	1:2.7
215 W LED	1.1:1	1:1.4

Table 20. HPS vs LED – Economic Analysis Summary

CHAPTER 5. PRIVATIZATION OF LIGHTING SYSTEM DESIGN, CONSTRUCTION AND MAINTENANCE – ECONOMIC ANALYSIS

An economic analysis comparing various PPP options for design, construction and maintenance of roadway lighting systems is presented in this chapter.

5.1. Public Private Partnership (PPP) Scenarios and Economic Analysis

The design, construction and maintenance of roadway lighting systems could be done by NCDOT or a design consulting firm and private construction / maintenance contractor. The current practice adopted by NCDOT is that NCDOT designs and maintains roadway lighting systems, while the construction is done by a private contractor generally as part of a roadway project contract. Privatizing design, construction and maintenance of roadway lighting systems or some of these tasks may yield economic benefits. An economic analysis was hence conducted to evaluate various scenarios and recommend the most viable option. Table 21 outlines various PPP scenarios that were considered for economic analysis in this research.

Scenario	Description
Scenario 1	Construction by a private firm; Design and maintenance by NCDOT.
Scenario 2	Design, construction and maintenance by NCDOT.
Scenario 3	Design, construction and maintenance by private firms.
Scenario 4	Design and construction by NCDOT; Maintenance by a private firm.
Scenario 5	Design and construction by private firms; Maintenance by NCDOT.
Scenario 6	Design by NCDOT; Construction and maintenance by private firm.
Scenario 7	Design by a private firm; Construction and maintenance by NCDOT.
Scenario 8	Construction by NCDOT; Design and maintenance by private firm

Table 21. Public Private Partnership (PPP) Scenarios for Economic Analysis

The design, installation and maintenance of HPS luminaires was considered for analysis. A roadway lighting system typically has a minimum service life of 25 years. The lighting design cost is a small percentage of the lighting system construction cost. A lighting system usually does not require redesign/renovation unless either it nears the end of the service life or if significant roadway redesign is planned, causing conflicts to existing lighting system. The working life of HPS luminaires is 3 years. Though these luminaires are relamped (maintenance) every 3 years, the steel pole and electrical conductors last till the end of the service life (25 years). Therefore, the life of design and construction is considered as 25 years, while the life of maintenance is considered as 3 years.

Cost estimates and bid prices for design, construction and maintenance of roadway lighting system were obtained from NCDOT (both NCDOT and private firm estimates). The roadway lighting design and construction costs are initial one-time capital costs, while maintenance estimates are annual maintenance costs. Table 22 shows cost estimates by category.

A 4% interest rate was used to convert the cost estimates to equivalent monthly cost estimates. Table 23 shows equivalent monthly cost estimates by category.

Cost Category	**Luminaire Fixture Type**		
	High Mast (100-ft, 750 W HPS)	**Twin-Arm (45-ft, 400 W HPS)**	**Single-Arm (45-ft, 400 W HPS)**
Design (DOT)	$660	$100	$70
Design (Private firm)	$1,320	$200	$140
Construction (DOT)	$53,000	$8,000	$5,500
Construction (Private firm)	$49,000	$7,400	$5,100
Annual maintenance (DOT)	$740	$110	$80
Annual maintenance (Private firm)	$850	$130	$90

Table 22. Cost Estimates for Roadway Lighting by Category

Cost Category	Luminaire Fixture Type		
	High Mast (100-ft, 750 W HPS)	**Twin-Arm (45-ft, 400 W HPS)**	**Single-Arm (45-ft, 400 W HPS)**
Design (DOT)	$3.48	$0.53	$0.37
Design (Private firm)	$6.97	$1.06	$0.74
Construction (DOT)	$279.75	$42.23	$29.03
Construction (Private firm)	$258.64	$39.06	$26.92
Annual maintenance (DOT)	$63.01	$9.37	$6.81
Annual maintenance (Private firm)	$72.38	$11.07	$7.66

Table 23. Equivalent Monthly Cost Estimates for Roadway Lighting by Category

The equivalent monthly cost estimates shown in Table 23 were used to compute estimated equivalent monthly cost for each scenario. Table 24 summarizes equivalent monthly total costs for high mast, twin arm and single arm roadway lighting systems obtained from economic analysis for various scenarios.

Results obtained indicate that current practice of roadway lighting design and maintenance by NCDOT and construction by private firm (scenario 1; base case) is an equally viable option as maintenance by NCDOT and roadway lighting design and construction by private firms. Roadway lighting design by NCDOT and construction and maintenance by private firms is as economical as privatizing design, construction and maintenance of roadway lighting systems. Adopting these scenarios would result in a marginal increase in costs to NCDOT. Other considered options were not observed to be economically beneficial. Trends in results obtained are generally consistent for high mast, twin arm or single arm roadway lighting systems.

Scenario	Const - Pvt, Des & Maint - NCDOT	All - NCDOT	All - Pvt	Des & Const - NCDOT, Maint - Pvt	Des & Const - Pvt, Maint - NCDOT	Des - NCDOT, Const & Maint - Pvt	Des - Pvt, Const & Maint - NCDOT	Const - NCDOT, Des & Maint - Pvt
High Mast (100-ft, 750 W HPS)								
Equivalent monthly design cost	3	3	7	3	7	3	7	7
Equivalent monthly construction cost	259	280	259	280	259	259	280	280
Equivalent monthly maintenance cost	63	63	72	72	63	72	63	72
Equivalent monthly total cost	322	343	331	352	322	331	343	352
Twin Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	1	1	1	1	1	1	1	1
Equivalent monthly construction cost	39	42	39	42	39	39	42	42
Equivalent monthly maintenance cost	9	9	11	11	9	11	9	11
Equivalent monthly total cost	48	52	50	53	48	50	52	53
Single Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	0	0	1	0	1	0	1	1
Equivalent monthly construction cost	27	29	27	29	27	27	29	29
Equivalent monthly maintenance cost	7	7	8	8	7	8	7	8
Equivalent monthly total cost	34	36	35	37	34	35	36	37

Note: Const is construction, Des is design, and Maint is maintenance; Pvt is private firm and NCDOT is North Carolina Department of Transportation.

Table 26. Results from Analysis of Selected Public Private Partnership Scenarios

5.2. Sensitivity Analysis

The results obtained from economical analysis are based on estimates from NCDOT and bid prices. They could vary over time and market conditions. Ideally, such variations should have minimal impact on practices adopted by NCDOT. Sensitivity analysis was hence conducted to examine the affects of these variations on results obtained from economical analysis. Twelve additional analyses were conducted in addition to base case using gathered cost estimates discussed in the previous section. In each analysis, either the roadway lighting design cost, the construction cost or the maintenance cost is increased or decreased by 10% when compared to the base case. Table 25 summarizes descriptions of various sensitivity analyses considered in this research.

Tables 26 to 37 summarize equivalent monthly total costs for high mast, twin arm and single arm roadway lighting systems obtained from sensitivity analysis for various scenarios. Figures 1, 2 and 3 show trends in estimates from sensitivity analysis for high mast, twin arm and single arm lighting systems, respectively. It can be observed from the tables and figures that results are generally insensitive to roadway lighting design and maintenance costs. However, they are sensitive to construction cost.

Analysis	Description
Analysis 1	Base case using gathered cost estimates
Analysis 2	NCDOT design cost increased by 10%
Analysis 3	NCDOT design cost decreased by 10%
Analysis 4	Private firm design cost increased by 10%
Analysis 5	Private firm design cost decreased by 10%
Analysis 6	NCDOT construction cost increased by 10%
Analysis 7	NCDOT construction cost decreased by 10%
Analysis 8	Private firm construction cost increased by 10%
Analysis 9	Private firm construction cost decreased by 10%
Analysis 10	NCDOT maintenance cost increased by 10%
Analysis 11	NCDOT maintenance cost decreased by 10%
Analysis 12	Private firm maintenance cost increased by 10%
Analysis 13	Private firm maintenance cost decreased by 10%

Table 25. Sensitivity Analyses Descriptions

Scenario	Const - Pvt, Des & Maint - NCDOT	All - NCDOT	All - Pvt	Des & Const - NCDOT, Maint - Pvt	Des & Const - Pvt, Maint - NCDOT	Des - NCDOT, Const & Maint - Pvt	Des - Pvt, Const & Maint - NCDOT	Const - NCDOT, Des & Maint - Pvt
High Mast (100-ft, 750 W HPS)								
Equivalent monthly design cost	4	4	7	4	7	4	7	7
Equivalent monthly construction cost	259	280	259	280	259	259	280	280
Equivalent monthly maintenance cost	63	63	72	72	63	72	63	72
Equivalent monthly total cost	322	343	331	352	322	331	343	352
Twin Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	1	1	1	1	1	1	1	1
Equivalent monthly construction cost	39	42	39	42	39	39	42	42
Equivalent monthly maintenance cost	9	9	11	11	9	11	9	11
Equivalent monthly total cost	48	52	50	53	48	50	52	53
Single Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	0	0	1	0	1	0	1	1
Equivalent monthly construction cost	27	29	27	29	27	27	29	29
Equivalent monthly maintenance cost	7	7	8	8	7	8	7	8
Equivalent monthly total cost	34	36	35	37	34	35	36	37

Note: Const is construction, Des is design, and Maint is maintenance; Pvt is private firm and NCDOT is North Carolina Department of Transportation.

Table 26. Results from Analysis - NCDOT Design Cost Increased by 10%

Scenario	Const - Pvt, Des & Maint - NCDOT	All - NCDOT	All - Pvt	Des & Const - NCDOT, Maint - Pvt	Des & Const - Pvt, Maint - NCDOT	Des - NCDOT, Const & Maint - Pvt	Des - Pvt, Const & Maint - NCDOT	Const - NCDOT, Des & Maint - Pvt
High Mast (100-ft, 750 W HPS)								
Equivalent monthly design cost	3	3	7	3	7	3	7	7
Equivalent monthly construction cost	259	280	259	280	259	259	280	280
Equivalent monthly maintenance cost	63	63	72	72	63	72	63	72
Equivalent monthly total cost	322	343	331	352	322	331	343	352
Twin Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	0	0	1	0	1	0	1	1
Equivalent monthly construction cost	39	42	39	42	39	39	42	42
Equivalent monthly maintenance cost	9	9	11	11	9	11	9	11
Equivalent monthly total cost	48	52	50	53	48	50	52	53
Single Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	0	0	1	0	1	0	1	1
Equivalent monthly construction cost	27	29	27	29	27	27	29	29
Equivalent monthly maintenance cost	7	7	8	8	7	8	7	8
Equivalent monthly total cost	34	36	35	37	34	35	36	37

Note: Const is construction, Des is design, and Maint is maintenance; Pvt is private firm and NCDOT is North Carolina Department of Transportation.

Table 27. Results from Analysis - NCDOT Design Cost Decreased by 10%

Scenario	Const - Pvt, Des & Maint - NCDOT	All - NCDOT	All - Pvt	Des & Const - NCDOT, Maint - Pvt	Des & Const - Pvt, Maint - NCDOT	Des - NCDOT, Const & Maint - Pvt	Des - Pvt, Const & Maint - NCDOT	Const - NCDOT, Des & Maint - Pvt
High Mast (100-ft, 750 W HPS)								
Equivalent monthly design cost	3	3	8	3	8	3	8	8
Equivalent monthly construction cost	259	280	259	280	259	259	280	280
Equivalent monthly maintenance cost	63	63	72	72	63	72	63	72
Equivalent monthly total cost	322	343	331	352	322	331	343	352
Twin Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	1	1	1	1	1	1	1	1
Equivalent monthly construction cost	39	42	39	42	39	39	42	42
Equivalent monthly maintenance cost	9	9	11	11	9	11	9	11
Equivalent monthly total cost	48	52	50	53	48	50	52	53
Single Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	0	0	1	0	1	0	1	1
Equivalent monthly construction cost	27	29	27	29	27	27	29	29
Equivalent monthly maintenance cost	7	7	8	8	7	8	7	8
Equivalent monthly total cost	34	36	35	37	34	35	36	37

Note: Const is construction, Des is design, and Maint is maintenance; Pvt is private firm and NCDOT is North Carolina Department of Transportation.

Table 28. Results from Analysis - Private Firm Design Cost Increased by 10%

Scenario	Const - Pvt, Des & Maint - NCDOT	All - NCDOT	All - Pvt	Des & Const - NCDOT, Maint - Pvt	Des & Const - Pvt, Maint - NCDOT	Des - NCDOT, Const & Maint - Pvt	Des - Pvt, Const & Maint - NCDOT	Const - NCDOT, Des & Maint - Pvt
High Mast (100-ft, 750 W HPS)								
Equivalent monthly design cost	3	3	6	3	6	3	6	6
Equivalent monthly construction cost	259	280	259	280	259	259	280	280
Equivalent monthly maintenance cost	63	63	72	72	63	72	63	72
Equivalent monthly total cost	322	343	331	352	322	331	343	352
Twin Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	1	1	1	1	1	1	1	1
Equivalent monthly construction cost	39	42	39	42	39	39	42	42
Equivalent monthly maintenance cost	9	9	11	11	9	11	9	11
Equivalent monthly total cost	48	52	50	53	48	50	52	53
Single Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	0	0	1	0	1	0	1	1
Equivalent monthly construction cost	27	29	27	29	27	27	29	29
Equivalent monthly maintenance cost	7	7	8	8	7	8	7	8
Equivalent monthly total cost	34	36	35	37	34	35	36	37

Note: Const is construction, Des is design, and Maint is maintenance; Pvt is private firm and NCDOT is North Carolina Department of Transportation.

Table 29. Results from Analysis - Private Firm Design Cost Decreased by 10%

Scenario	Const - Pvt, Des & Maint - NCDOT	All - NCDOT	All - Pvt	Des & Const - NCDOT, Maint - Pvt	Des & Const - Pvt, Maint - NCDOT	Des - NCDOT, Const & Maint - Pvt	Des - Pvt, Const & Maint - NCDOT	Const - NCDOT, Des & Maint - Pvt
High Mast (100-ft, 750 W HPS)								
Equivalent monthly design cost	3	3	7	3	7	3	7	7
Equivalent monthly construction cost	259	308	259	308	259	259	308	308
Equivalent monthly maintenance cost	63	63	72	72	63	72	63	72
Equivalent monthly total cost	322	371	331	380	322	331	371	380
Twin Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	1	1	1	1	1	1	1	1
Equivalent monthly construction cost	39	46	39	46	39	39	46	46
Equivalent monthly maintenance cost	9	9	11	11	9	11	9	11
Equivalent monthly total cost	48	56	50	58	48	50	56	58
Single Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	0	0	1	0	1	0	1	1
Equivalent monthly construction cost	27	32	27	32	27	27	32	32
Equivalent monthly maintenance cost	7	7	8	8	7	8	7	8
Equivalent monthly total cost	34	39	35	40	34	35	39	40

Note: Const is construction, Des is design, and Maint is maintenance; Pvt is private firm and NCDOT is North Carolina Department of Transportation.

Table 30. Results from Analysis - NCDOT Construction Cost Increased by 10%

Scenario	Const - Pvt, Des & Maint - NCDOT	All - NCDOT	All - Pvt	Des & Const - NCDOT, Maint - Pvt	Des & Const - Pvt, Maint - NCDOT	Des - NCDOT, Const & Maint - Pvt	Des - Pvt, Const & Maint - NCDOT	Const - NCDOT, Des & Maint - Pvt
High Mast (100-ft, 750 W HPS)								
Equivalent monthly design cost	3	3	7	3	7	3	7	7
Equivalent monthly construction cost	259	252	259	252	259	259	252	252
Equivalent monthly maintenance cost	63	63	72	72	63	72	63	72
Equivalent monthly total cost	322	315	331	324	322	331	315	324
Twin Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	1	1	1	1	1	1	1	1
Equivalent monthly construction cost	39	38	39	38	39	39	38	38
Equivalent monthly maintenance cost	9	9	11	11	9	11	9	11
Equivalent monthly total cost	48	47	50	49	48	50	47	49
Single Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	0	0	1	0	1	0	1	1
Equivalent monthly construction cost	27	26	27	26	27	27	26	26
Equivalent monthly maintenance cost	7	7	8	8	7	8	7	8
Equivalent monthly total cost	34	33	35	34	34	35	33	34

Note: Const is construction, Des is design, and Maint is maintenance; Pvt is private firm and NCDOT is North Carolina Department of Transportation.

Table 31. Results from Analysis - NCDOT Construction Cost Decreased by 10%

Scenario	Const - Pvt, Des & Maint - NCDOT	All - NCDOT	All - Pvt	Des & Const - NCDOT, Maint - Pvt	Des & Const - Pvt, Maint - NCDOT	Des - NCDOT, Const & Maint - Pvt	Des - Pvt, Const & Maint - NCDOT	Const - NCDOT, Des & Maint - Pvt
High Mast (100-ft, 750 W HPS)								
Equivalent monthly design cost	3	3	7	3	7	3	7	7
Equivalent monthly construction cost	285	280	285	280	285	285	280	280
Equivalent monthly maintenance cost	63	63	72	72	63	72	63	72
Equivalent monthly total cost	348	343	357	352	348	357	343	352
Twin Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	1	1	1	1	1	1	1	1
Equivalent monthly construction cost	43	42	43	42	43	43	42	42
Equivalent monthly maintenance cost	9	9	11	11	9	11	9	11
Equivalent monthly total cost	52	52	54	53	52	54	52	53
Single Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	0	0	1	0	1	0	1	1
Equivalent monthly construction cost	30	29	30	29	30	30	29	29
Equivalent monthly maintenance cost	7	7	8	8	7	8	7	8
Equivalent monthly total cost	36	36	37	37	36	37	36	37

Note: Const is construction, Des is design, and Maint is maintenance; Pvt is private firm and NCDOT is North Carolina Department of Transportation.

Table 32. Results from Analysis - Private Firm Construction Cost Increased by 10%

Scenario	Const - Pvt, Des & Maint - NCDOT	All - NCDOT	All - Pvt	Des & Const - NCDOT, Maint - Pvt	Des & Const - Pvt, Maint - NCDOT	Des - NCDOT, Const & Maint - Pvt	Des - Pvt, Const & Maint - NCDOT	Const - NCDOT, Des & Maint - Pvt
High Mast (100-ft, 750 W HPS)								
Equivalent monthly design cost	3	3	7	3	7	3	7	7
Equivalent monthly construction cost	233	280	233	280	233	233	280	280
Equivalent monthly maintenance cost	63	63	72	72	63	72	63	72
Equivalent monthly total cost	296	343	305	352	296	305	343	352
Twin Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	1	1	1	1	1	1	1	1
Equivalent monthly construction cost	35	42	35	42	35	35	42	42
Equivalent monthly maintenance cost	9	9	11	11	9	11	9	11
Equivalent monthly total cost	45	52	46	53	45	46	52	53
Single Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	0	0	1	0	1	0	1	1
Equivalent monthly construction cost	24	29	24	29	24	24	29	29
Equivalent monthly maintenance cost	7	7	8	8	7	8	7	8
Equivalent monthly total cost	31	36	32	37	31	32	36	37

Note: Const is construction, Des is design, and Maint is maintenance; Pvt is private firm and NCDOT is North Carolina Department of Transportation.

Table 33. Results from Analysis - Private Firm

Construction Cost Decreased by 10%

Scenario	Const - Pvt, Des & Maint - NCDOT	All - NCDOT	All - Pvt	Des & Const - NCDOT, Maint - Pvt	Des & Const - Pvt, Maint - NCDOT	Des - NCDOT, Const & Maint - Pvt	Des - Pvt, Const & Maint - NCDOT	Const - NCDOT, Des & Maint - Pvt
High Mast (100-ft, 750 W HPS)								
Equivalent monthly design cost	3	3	7	3	7	3	7	7
Equivalent monthly construction cost	259	280	259	280	259	259	280	280
Equivalent monthly maintenance cost	69	69	72	72	69	72	69	72
Equivalent monthly total cost	328	349	331	352	328	331	349	352
Twin Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	1	1	1	1	1	1	1	1
Equivalent monthly construction cost	39	42	39	42	39	39	42	42
Equivalent monthly maintenance cost	10	10	11	11	10	11	10	11
Equivalent monthly total cost	49	53	50	53	49	50	53	53
Single Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	0	0	1	0	1	0	1	1
Equivalent monthly construction cost	27	29	27	29	27	27	29	29
Equivalent monthly maintenance cost	7	7	8	8	7	8	7	8
Equivalent monthly total cost	34	37	35	37	34	35	37	37

Note: Const is construction, Des is design, and Maint is maintenance; Pvt is private firm and NCDOT is North Carolina Department of Transportation.

Table 34. Results from Analysis - NCDOT Maintenance Cost Increased by 10%

Scenario	Const - Pvt, Des & Maint - NCDOT	All - NCDOT	All - Pvt	Des & Const - NCDOT, Maint - Pvt	Des & Const - Pvt, Maint - NCDOT	Des - NCDOT, Const & Maint - Pvt	Des - Pvt, Const & Maint - NCDOT	Const - NCDOT, Des & Maint - Pvt
High Mast (100-ft, 750 W HPS)								
Equivalent monthly design cost	3	3	7	3	7	3	7	7
Equivalent monthly construction cost	259	280	259	280	259	259	280	280
Equivalent monthly maintenance cost	57	57	72	72	57	72	57	72
Equivalent monthly total cost	315	336	331	352	315	331	336	352
Twin Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	1	1	1	1	1	1	1	1
Equivalent monthly construction cost	39	42	39	42	39	39	42	42
Equivalent monthly maintenance cost	8	8	11	11	8	11	8	11
Equivalent monthly total cost	47	51	50	53	47	50	51	53
Single Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	0	0	1	0	1	0	1	1
Equivalent monthly construction cost	27	29	27	29	27	27	29	29
Equivalent monthly maintenance cost	6	6	8	8	6	8	6	8
Equivalent monthly total cost	33	35	35	37	33	35	35	37

Note: Const is construction, Des is design, and Maint is maintenance; Pvt is private firm and NCDOT is North Carolina Department of Transportation.

Table 35. Results from Analysis - NCDOT Maintenance Cost Decreased by 10%

Scenario	Const - Pvt, Des & Maint - NCDOT	All - NCDOT	All - Pvt	Des & Const - NCDOT, Maint - Pvt	Des & Const - Pvt, Maint - NCDOT	Des - NCDOT, Const & Maint - Pvt	Des - Pvt, Const & Maint - NCDOT	Const - NCDOT, Des & Maint - Pvt
High Mast (100-ft, 750 W HPS)								
Equivalent monthly design cost	3	3	7	3	7	3	7	7
Equivalent monthly construction cost	259	280	259	280	259	259	280	280
Equivalent monthly maintenance cost	63	63	80	80	63	80	63	80
Equivalent monthly total cost	322	343	338	359	322	338	343	359
Twin Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	1	1	1	1	1	1	1	1
Equivalent monthly construction cost	39	42	39	42	39	39	42	42
Equivalent monthly maintenance cost	9	9	12	12	9	12	9	12
Equivalent monthly total cost	48	52	51	54	48	51	52	54
Single Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	0	0	1	0	1	0	1	1
Equivalent monthly construction cost	27	29	27	29	27	27	29	29
Equivalent monthly maintenance cost	7	7	8	8	7	8	7	8
Equivalent monthly total cost	34	36	35	37	34	35	36	37

Note: Const is construction, Des is design, and Maint is maintenance; Pvt is private firm and NCDOT is North Carolina Department of Transportation.

Table 36. Results from Analysis - Private Firm Maintenance Cost Increased by 10%

Scenario	Const - Pvt, Des & Maint - NCDOT	All - NCDOT	All - Pvt	Des & Const - NCDOT, Maint - Pvt	Des & Const - Pvt, Maint - NCDOT	Des - NCDOT, Const & Maint - Pvt	Des - Pvt, Const & Maint - NCDOT	Const - NCDOT, Des & Maint - Pvt
High Mast (100-ft, 750 W HPS)								
Equivalent monthly design cost	3	3	7	3	7	3	7	7
Equivalent monthly construction cost	259	280	259	280	259	259	280	280
Equivalent monthly maintenance cost	63	63	65	65	63	65	63	65
Equivalent monthly total cost	322	343	324	345	322	324	343	345
Twin Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	1	1	1	1	1	1	1	1
Equivalent monthly construction cost	39	42	39	42	39	39	42	42
Equivalent monthly maintenance cost	9	9	10	10	9	10	9	10
Equivalent monthly total cost	48	52	49	52	48	49	52	52
Single Arm (45-ft, 400 W HPS)								
Equivalent monthly design cost	0	0	1	0	1	0	1	1
Equivalent monthly construction cost	27	29	27	29	27	27	29	29
Equivalent monthly maintenance cost	7	7	7	7	7	7	7	7
Equivalent monthly total cost	34	36	34	36	34	34	36	36

Note: Const is construction, Des is design, and Maint is maintenance; Pvt is private firm and NCDOT is North Carolina Department of Transportation.

Table 37. Results from Analysis - Private Firm Maintenance Cost Decreased by 10%

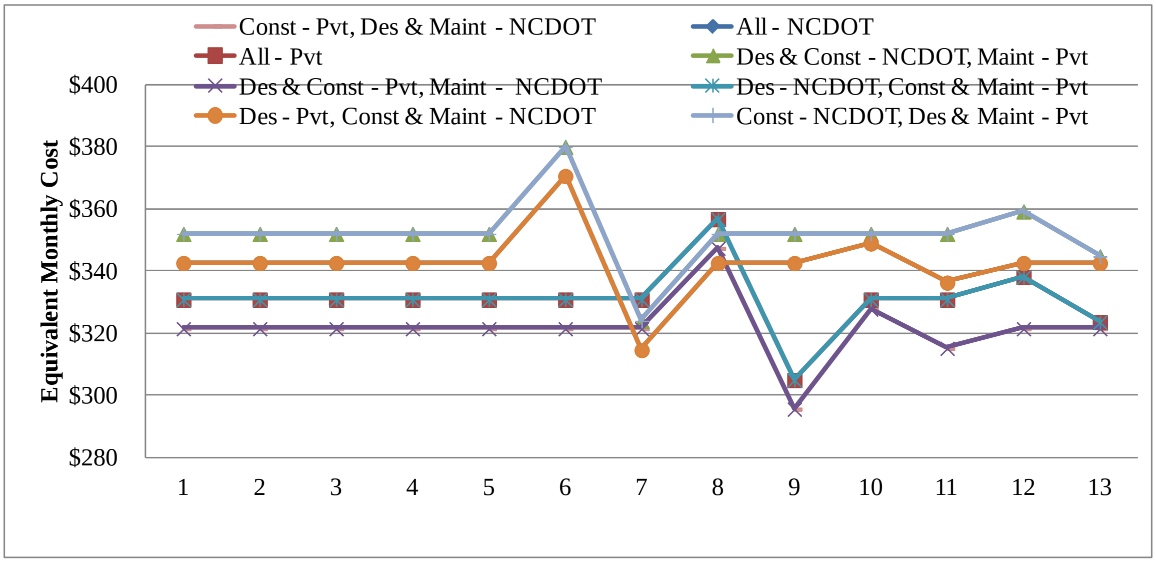

Figure 1. Results from Sensitivity Analysis - High Mast Lighting

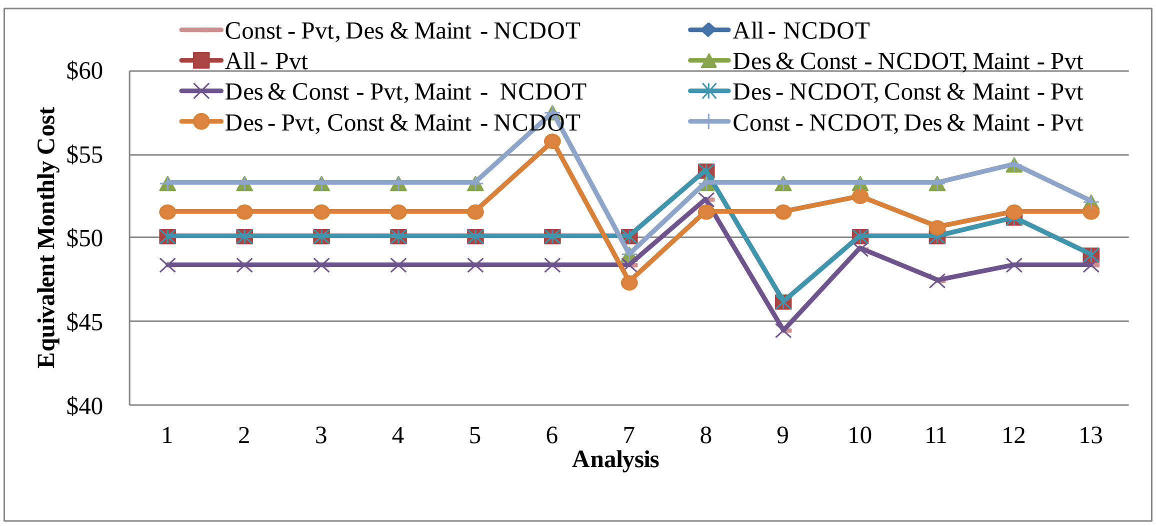

Figure 2. Results from Sensitivity Analysis - Twin Arm Lighting

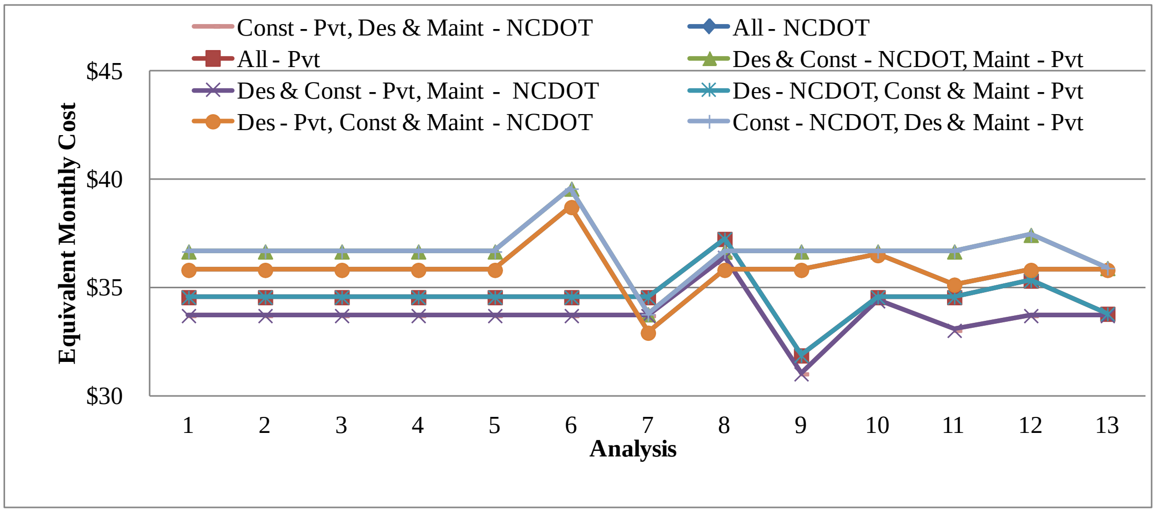

Figure 3. Results from Sensitivity Analysis - Single Arm Lighting

In general, results from sensitivity analysis support those obtained earlier from economic analysis. They indicate that current practice of design and maintenance by NCDOT and construction by private firm is still the most economically viable option. While roadway lighting design and construction by private firms and maintenance by NCDOT is an equally viable option, only roadway lighting design by NCDOT or privatizing roadway lighting design, construction and maintenance may result in a marginal increase of costs. A 10% decrease in NCDOT construction cost (if private firm construction cost remains constant) may bring down the total cost to lower than the base case (design and maintenance by NCDOT). The benefits, however, in this case are marginal. On the other hand, obtaining competitive bids and lowering private firm construction cost will lower the overall cost and maximize benefits to NCDOT.

CHAPTER 6. INTERCHANGE LIGHTING PRIORITIZATION TOOL

A discussion on NCDOT's current practice for prioritizing new interchange lighting installations, data collection along selected study corridors and identification of new factors for consideration, unlighted and lighted weights for each new factor, development of updated lighting priority index tool, and results comparing computations using current and updated lighting priority index tool are presented in this chapter.

6.1. NCDOT and Current Practice

NCDOT currently performs lighting evaluations in accordance with the "Total Design Process (TDP)" adopted from NCHRP Report 152 "Warrants for Highway Lighting" (Walton and Rowan, 1974). The TDP is a method of determining the cost-effectiveness of installing roadway lighting, and establishing a priority index to determine if investing state funds is justified. The priority index is a unit-less number computed by multiplying need (warrant) and benefit factors (traffic volume) and then dividing by the cost.

The warrant factor is computed using various geometric factors (ramp type, crossroad channelization, frontage roads, freeway lane width, freeway median width, number of freeway lanes, curves, grades and sight distance), operational factors (level-of-service and freeway volume), environmental factors (percent development, offset to development from traffic lanes, freeway lighting, and crossroad approach lighting), and night-to-day crash rate ratio. Each factor considered in the computation of warrants is divided into a maximum of five different ratings (categories 1 to 5) based on the complexity that the driver might encounter due to the factor. The rating of the factor is multiplied by the difference of unlighted and lighted weight for the factor to obtain the warranting points related to the factor. The warranting points of all factors are summed to compute the total interchange warranting points. The maximum number of points an interchange could have for geometric, operational, environmental and crash factors are 40.5, 30, 23.5 and 40, respectively. Table 38 shows interchange warranting condition tool (example) currently used by NCDOT.

TABLE B

INTERCHANGE SECTIONS

TIP PROJECT#: COUNTY: YEAR: 2012

ROADWAY SECTION: 11: I-77/I-277 Interchange

STATION FROM: N/A STATION TO: N/A LENGTH: N/A

PLACE AN "X" UNDER THE CORRESPONDING RATING #

CLASSIFICATION FACTOR		RATING 1	RATING 2	RATING 3	RATING 4	RATING 5	UNLIGHTED WEIGHT (A)	LIGHTED WEIGHT (B)	DIFFERENCE (A-B)	RATING x DIFFERENCE
GEOMETRIC FACTORS										
1-GF	RAMP TYPES	DIRECT	DIAMOND	BUTTON HOOKS CLOVERLEAFS	TRUMPET	SCISSORS AND LEFT SIDE EXIT	2	1	1	2
			X							
2-GF	CROSSROAD CHANNELIZATION	NONE		CONTINUOUS		AT INTERCHANGE INTERSECTIONS	2	1	1	3
				X						
3-GF	FRONTAGE ROADS	NONE		ONE-WAY		TWO-WAY	1.5	1	0.5	0.5
		X								
4-GF	FREEWAY LANE WIDTH	12		11		10	3	2.5	0.5	0.5
		X								
5-GF	FREEWAY MEDIAN WIDTH	>40'	24-40'	12-24'	4-12'	<4'	1	0.5	0.5	1.5
				X						
6-GF	# FREEWAY LANES	4 OR LESS		6		8 OR MORE	10	8	2	10
						X				
7-GF	MAIN LANE CURVES	1/2	1-2	2-3	3-4	4	10	8	2	2
		X								
8-GF	GRADES	3%	3-3.9%	4-4.9%	5-6.9%	>7%	3.2	2.8	0.4	0.4
		X								
9-GF	SIGHT DIST. CROSS ROAD INTERSECTION	1000'	700-1000'	500-700'	400-500'	<400'	2	1.8	0.2	0.2
		X								
									SUBTOTAL	20.1
OPERATIONAL FACTORS										
1-OF	LEVEL OF SERVICE	A	B	B-C	C-D	D-E	6	1	5	10
			X							
2-OF	TOTAL NIGHT VOLUME PER LANE	<1000	1000	2000	3000	4000	6	1	5	20
					X					
									SUBTOTAL	30
ENVIRONMENTAL FACTORS										
1-EF	%DEVELOPMENT	NONE	1 QUAD	2 QUAD	3 QUAD	4 QUAD	2	0.5	1.5	7.5
						X				
2-EF	OFFSET TO DEVELOP. FROM TRAFFIC LANES	>200'	150-200'	100-150'	50-100'	<50'	0.5	0.3	0.2	0.2
		X								
3-EF	CROSS ROAD APPROACH LIGHTING	NONE		PARTIAL		COMPLETE	3	2	1	3
				X						
4-EF	FREEWAY LIGHTING	NONE		INTERCHANGES ONLY		CONTINUOUS	5	3	2	6
				X						
									SUBTOTAL	16.7
ACCIDENTS										
1-AF	RATIO OF NIGHT TO DAY ACCIDENT RATES	<1.0	1.0-1.1	1.1-1.2	1.2-1.5	>1.5	10	2	8	32
					X					
									SUBTOTAL	32
					INTERCHANGE WARRANTING CONDITION = 75 POINTS				TOTAL	98.8

Table 38. Current Interchange Warranting Condition Tool - Example

The benefit factor (number of vehicles using the roadway at night) is based on 25% of the ADT received from traffic forecasters in the Statewide Planning Branch. The standardized design includes a combination of 100’ high masts and 45’ light standards with HPS luminaries and underground circuitry. The total estimated cost generally varies from $50,000 per pole to as high as $400,000 for an interchange.

Providing lighting at obsolete sections because of poor conditions and no traffic at night, due to closure of business or change in land use is cost prohibitive. The computed priority index is, therefore, compared to an accepted threshold value, below which investing funds is not justified. Funds are allocated on a priority basis if the threshold criterion is satisfied. The current threshold values used by NCDOT, which indicate the minimum requirements justifying lighting for interchange and continuous sections, are 62 and 100, respectively.

The NCHRP Report 152 “Warrants for Highway Lighting” (Walton and Rowan, 1974) is more than a 30 year-old guidebook that does not account for various factors that range from crash severity to traffic composition (percent heavy vehicles or freeway to ramp volume ratio) to other criteria that are essential for allocation of limited resources. A methodology was developed to identify new factors, categories and ratings for each factor and category, unlighted and lighted weights, and to update the lighting priority index tool.

6.2. Methodology

The methodology to identify new factors, weights and update the lighting priority index tool includes the following steps.

1. Select study corridors
2. Collect data
3. Identify new factors
4. Define categories and ratings for each new factor
5. Analyze crash data to determine unlighted and lighted weights for each new factor
6. Update interchange lighting priority index tool

6.2.1. Select Study Corridors

Nine study corridors with full access control in North Carolina were selected to collect data, identify new factors and compare results obtained from current and updated interchange lighting priority index tool. These nine study corridors include six Interstates and three US routes.

The selected corridors are spatially distributed throughout the state of North Carolina. Further, the study corridors were selected such that they are located in both rural and urban areas. Table 39 lists each selected study corridor, start milepost or crossroad, end milepost or crossroad, and county in which the study corridor is located.

Corridor	Start Milepost	End Milepost	Start Crossroad	End Crossroad	County
I-277	0	4.451	Entire Corridor		Mecklenburg
I-40	0	16			Haywood
I-485	47	65			Mecklenburg
I-77	10	30			Mecklenburg
I-95	16	27			Robeson
I-85	10	40			Mecklenburg
US-64/264			I-440	NC-96	Wake
US-70			NC-41	US-17	Craven
US-74			NC-180	I-85	Cleveland

Table 39. Selected Study Corridors

6.2.2. Collect Data

Data was collected along each selected study corridor, in particular at interchanges. Crash data (from year 2006 to 2011) for the segments was obtained from NCDOT. Various geometric, land use, lighting and traffic characteristics along the corridors were collected through field visits and using Google Earth. The selected number of interchanges along each selected study corridor is shown in Table 40.

Interchanges were distinguished based on the exit number. As each type of interchange has its own special characteristics, a partial cloverleaf interchange within a diamond interchange was considered as two separate interchanges. Also, full cloverleaf interchanges within a diamond interchange were considered as two separate interchanges. Ramps that have different exit numbers or connect different roads were considered as separate interchanges. The total number of such interchanges along the selected study corridors adds to 80.

Corridor	# Interchanges
I-277	9
I-40	2
I-485	9
I-77	17
I-95	5
I-85	21
US-64/264	9
US-70	4
US-74	4

Table 40. Number of Interchanges Along Selected Study Corridors

Traffic data were collected at 25 interchanges between 10 PM and 2 PM for at least half an hour through field visits. This was primarily done to observe if 25% of traffic volume occurs at night. Freeway volume and ramp volume were collected at 2 interchanges each along I-277 and I-40, and at 3 interchanges on each of the remaining corridors. Observed traffic data indicates that night-time traffic volume estimates are less than 15% of ADT (from NCDOT travel survey maps) at most of the selected interchanges. The percent of heavy vehicle volume at night-time was observed to be significantly high (nearly 50% of traffic volume observed) at 7 interchanges with an overall average close to 25% of night-time traffic volume. Ramp volumes were high at interchanges with large number of developments. It was observed that ramp volume at interchanges with no developments within their proximity were less when compared to ramp volume at interchanges with developments within their proximity.

Land use characteristics except business operation hours were obtained from Google Earth. Most of the land uses within the vicinity of interchanges are residential and commercial developments. Freeway volume and ramp volume were comparatively high at interchanges in urban areas than at interchanges in rural areas (primarily due to commercial activity open at night in urban areas). Urban areas also have residential developments near the freeway resulting in a relatively higher ramp volume at night. All commercial establishments except gas stations near selected interchanges were observed to be closed after 10:00 PM.

All geometric characteristics except road markings and gradient were captured from Google Earth. Road markings and gradient were collected at each interchange along all selected study corridors. All the selected study corridors have relatively flat terrain (less than 3% grade). None of the interchanges along the selected study corridors have characteristics of a critical horizontal curve.

All lighting characteristics except pole spacing were collected through field visits. Illuminance was measured using a luminance meter. Digital Illuminance / Light Meter LX1330B with a range of 0 to 20,000 footcandle was used to measure the illuminance. Freeway lighting and cross roadway lighting was differentiated as complete and partial. Type of roadway lights - HPS or any other type, presence of high mast lighting and lighting from adjacent developments were also noted.

A sample data collection sheet used in this research is shown in Table 41. Tables 42 and 43 summarize acceleration lane length, deceleration lane length, signboard placement distance, number of fatal, injury type “A”, injury type “B”, injury type “C”, PDO and total crashes, night-to-day crash rate ratio (defined as percent of night-time crashes to percent of day-time crashes divided by percent of night-time traffic volume to percent of day-time traffic volume), luminous index, % heavy vehicles and ramp volume ratio (defined as ramp volume to freeway through volume) at interchanges with lighting system and without lighting system, respectively. The percent heavy vehicles and ramp volume ratio for interchanges where field data were not collected are averages computed based on data for the respective corridor.

6.2.3. Identify New Factors

The crashes at interchanges are typically associated to merging, diverging and weaving maneuvers. Providing adequate acceleration and deceleration lane lengths (as a function of speed limit) will provide ample time for drivers to complete these maneuvers, reduce the number of crashes and enhance safety at interchanges. The lack of roadway lighting further aggravates the likelihood of night-time crashes. These two factors were therefore considered for further analysis and possible inclusion in the updated lighting priority index tool.

The placement of signboard too may have an effect on diverging maneuver at interchanges. If the signboard is placed close to the interchange, the time available for the driver to identify the path of travel and take a decision to diverge from the freeway traffic is relatively less. The lack of roadway lighting at interchanges where signboards are placed close to interchanges would worsen the situation. Therefore, the distance of signboard placement from the interchange was considered as vital for improving safety at interchanges and was considered for further analysis and possible inclusion in the updated lighting priority index tool.

Crash severity is one major factor that was not considered in the past while prioritizing interchanges for roadway lighting. Fatal crashes result in loss of lives and higher monetary disbenefits than all other types of crashes. The lack of roadway lighting limits visibility at interchanges and increases the probability of severe crashes. Improving roadway lighting at interchanges with higher number of severe crashes also yields more benefits. Further, night-to-day crash rate ratio may be more biased towards interchanges with fewer numbers of crashes or low traffic volume. The crash severity was therefore considered for further analysis and possible inclusion in the updated lighting priority index tool.

Illumination at interchanges generally would improve security and safety. A low illumination level would result in lack of visibility at night-time and could be probable cause of crashes. The illuminance level at interchanges was therefore considered for further analysis and possible inclusion in the updated lighting priority index tool.

Traffic composition is another important factor that could have a bearing on the number of crashes at interchanges. Safety problems could be further aggravated due to the presence of heavy vehicles or truck traffic. The ramp vehicular volume too plays a major role in increasing crashes at interchanges. The lack of roadway lighting worsens the condition and results in more disbenefits in such situations. The percent of heavy vehicles and ramp volume ratio were therefore considered for further analysis and possible inclusion in the updated lighting priority index tool.

PROJECT TITLE: NC ROADWAY LIGHTING NEEDS ASSESSMENT, MAINTENANCE PRIORITIZATION TOOL AND PERFORMANCE MEASURES					
Corridor:					
Interchange #:					
Interchange name:					
# ramps:					
Date:					
Time:					
Geometric					
	NB / EB		SB / WB		
Freeway lane width					
# Freeway lanes					
Horizontal curve					
Grade					
Pavement type					
Median type					
	Right	Left	Right	Left	
Shoulder width					
	Onramp	Offramp	Onramp	Offramp	
Ramp type					
Ramp length					
Ramp lane width					
Ramp # lanes					
Acceleration/decceleration lane					
Exit-entry ramp distances for clover leaf interchanges					
Sign-board placement from ramp					
Cross-street channelization					
Cross-street intersection sight distance					
Frontage road					
Skewness					
Road markings					
Land-use					
Development (Yes/No) - each quadrant					
	Res.	Food	Gas	Other	
Land-use					
	NB / EB		SB / WB		
Development					
Offset to development from traffic lanes					
Businesses operating till 10 PM					
Businesses operating till 12 AM					
Businesses operating 24 hours					
Lighting					
	Onramp	Offramp	Onramp	Offramp	
Freeway lighting					
Cross-street lighting					
Sign visibility					
Lighting from adjacent development					
Illuminance and Luminance					
Luminaire type					
Pole spacing					
Traffic					
	NB / EB		SB / WB		
Night traffic volume - freeway					
Speed limit - freeway					
Traffic mix (% heavy vehicles)					
	Onramp	Offramp	Onramp	Offramp	
Night traffic volume - ramp					
Speed limit - ramp					

Table 41. Data Collection Sheet

Interchange	Acceleration Lane Length	Deceleration Lane Length	Signboard Placement Distance	Night-time # Crashes					Total # Crashes	Night/Day Crash Rate Ratio	LI	%HV	RVR
				K	A	B	C	PDO					
I-77 / I-277	3	3	1	1	2	9	37	101	469	1.41	2.1	8.4	0.5
I-77 / Lassalle St	3	3	1	0	0	5	27	79	419	1.08	3.9	9.2	0.11
I-77 / NC-24	2	2	2	0	0	4	20	62	277	1.35	5.5	20.3	0.16
I-40 / Fines Creek Rd	1	1	1	0	0	0	0	11	35	1.38	0.1	67.3	0
I-85 / Cox Rd	2	3	2	1	1	5	2	20	100	1.23	0.1	49.9	0.05
I-95 / S Caton Rd	3	2	1	1	0	3	4	27	130	1.11	13.3	31.8	0.09
I-95 / N Roberts Ave	2	2	1	1	0	1	7	17	52	3.00	9	29.3	0.17
I-95 / Fayetville Rd	2	2	1	0	0	1	10	23	98	1.59	11.5	29	0.16
I-277 / S College St	1	3	1	0	0	1	1	10	35	1.57	8.1	18.6	0.28
I-277 / N Church St	1	1	1	0	0	1	1	9	37	1.27	6.2	4.9	0.12
I 485 / US-74	3	2	2	0	0	1	2	22	49	3.13	0.1	30.7	0.32
I-77 / W Morehead St	3	3	1	1	1	5	21	35	217	1.23	5.9	12.7	0.25
I-77 / W Trade St	3	3	1	1	3	10	36	84	432	1.35	2.1	12.7	0.25
I-77 / I-85	1	1	1	0	0	29	59	161	768	1.44	4.1	12.7	0.25
I-77 / NC-21 (Sunset Rd)	1	1	1	2	2	5	35	84	569	0.87	4.4	12.7	0.25
I-77 / I-485	2	3	2	0	0	0	2	20	81	1.12	0.1	12.7	0.25
I-77 / Gilead Rd	3	3	1	0	0	10	9	45	247	1.05	0.4	12.7	0.25
I-77 / NC-73 (Sam Furr Rd)	3	3	1	0	1	3	10	31	191	0.92	13.2	12.7	0.25
I-77 / Catabwa Ave	3	2	1	0	0	2	9	37	214	0.87	10	12.7	0.25
I-77 / Griffith Rd	2	2	1	0	0	1	6	14	93	0.88	14.9	12.7	0.25
I-85 / Edgewood Rd	2	2	1	0	0	1	4	14	78	0.97	0.1	35.3	0.15
I-85 / NC-274	3	1	3	0	1	3	5	19	68	2.10	0.5	35.3	0.14
I-85 / Sam Wilson Rd	2	2	1	1	0	4	19	53	194	1.97	2.6	35.3	0.14
I-85 / Little Rock Rd	2	2	1	0	2	2	11	26	139	1.26	10.4	35.3	0.14
I-85 / Mulbery Church Rd	2	1	1	1	0	4	5	20	130	0.90	9.3	35.3	0.14
I-85 / Tuckaseegee Rd	2	1	3	0	2	8	14	45	251	1.14	5.4	35.3	0.14
I-85 / NC-27	3	1	3	0	2	8	14	45	219	1.38	5.4	35.3	0.14
I-85 / Glenwood Drv	3	1	3	0	2	7	14	33	263	0.81	10	35.3	0.14
I-85 / NC-16	2	1	3	0	0	4	19	47	226	1.35	3.2	35.3	0.14
I-85 / Beattis Ford Rd	3	3	1	1	0	6	5	21	102	1.43	10.7	35.3	0.14
I-85 / Statesville Ave Rd	3	3	1	3	2	19	49	154	841	1.11	6.7	35.3	0.14
I-85 / N Graham St	2	2	2	0	0	0	6	11	106	0.57	6.7	35.3	0.14
I-95 / Carthage Rd	1	1	1	1	0	0	6	18	68	1.74	9.3	30.1	0.14
I-95 / US-301	1	1	1	0	1	1	5	11	62	1.23	11.5	30.1	0.14
I-277 / I-77	2	3	2	0	0	2	15	18	104	1.52	2.5	11.8	0.13
I-277 / South Blvd	3	3	1	0	0	1	3	7	28	1.94	8.1	11.8	0.13
I-277 / NC-16	3	2	1	0	1	5	7	17	173	0.63	7.3	11.8	0.13
I-277 / N Caldwell St	2	2	1	0	0	0	1	3	11	1.71	1	11.8	0.13
I-277 / I-77	1	3	1	0	0	0	1	2	5	4.50	1.5	11.8	0.13

Note:
K, A, B, C and O are fatal, injury type "A", "B" and "C" and PDO crashes, respectively.
1, 2, 3 for acceleration lane length and deceleration lane length indicate < 250 feet, 250 to 750 feet and > 750 feet, respectively.
1, 2, 3 for signboard placement distance indicate < 1,320 feet, 1,320 to 2,640 feet and 2,640 to 5,280 feet, respectively.
LI, %HV and RVR are luminour index, % heavy vehicles and ramp volume ratio, respectively.

Table 42. Interchanges with Lighting Systems – Data Summary

Interchange	Acceleration Lane Length	Deceleration Lane Length	Signboard Placement Distance	Night-time # Crashes					Total # Crashes	Night/Day Crash Rate Ratio	LI	%HV	RVR
				K	A	B	C	PDO					
I-40 / Cold Springs Creek Rd	1	1	1	0	0	2	4	27	89	1.77	0.1	66.4	0
I-85 / I-485	3	3	1	0	0	7	17	63	205	2.21	0.1	25.2	0.12
I-85 / I-77	3	3	1	2	0	10	14	32	179	1.44	3.6	30.8	0.25
I-485 / Providence Rd	3	3	3	0	2	2	5	28	134	1.14	0.1	28.9	0.23
I-485 / Johnston Rd	3	3	3	0	0	2	6	48	203	1.14	0.1	11	0.13
US-64 / I-540	3	3	3	0	0	0	0	1	2	3.00	0.1	6.15	0.29
US-64 / Knightdale Rd	2	3	1	0	0	1	4	16	56	1.80	0.6	9.62	0.15
US-64 / N Arendell Ave	2	2	1	0	0	2	1	31	108	1.38	0.1	15.4	0.23
US-70 / NC-41	2	2	1	0	0	1	0	3	6	6.00	0.1	21	0.18
US-70 / Clarks Rd	2	1	1	0	0	2	5	18	61	2.08	0.1	12.4	0.46
US-70 / Country Club Rd	2	1	3	0	0	0	0	0	0		1.7	0	0.14
US-74 / NC161	3	1	3	0	0	0	0	12	31	1.89	0.1	16.9	0.11
US-74 / Oak Grove Rd	3	1	3	1	0	0	5	14	47	2.22	0.1	18.4	0.06
US-74 / Shelby Rd	2	1	3	2	1	1	3	10	48	1.65	0.1	33	0.11
I-77 / W 5th St	2	2	2	2	7	20	79	185	903	1.44	1.7	12.7	0.25
I-85 / US-321	1	1	1	0	0	3	15	36	192	1.17	0.1	35.3	0.14
I-85 / NC-279	3	2	2	0	1	5	13	15	121	1.17	0.2	35.3	0.14
I-85 / S Main St	3	3	3	0	0	6	13	48	264	1.02	0.2	35.3	0.14
I-85 / NC-7	3	3	3	0	1	4	15	38	184	1.38	0.1	35.3	0.14
I-85 / McAdenville / N Main St	3	3	3	2	0	4	6	35	141	1.50	0.1	35.3	0.14
I-85 / NC-273	2	3	1	0	0	3	11	91	338	1.35	0.1	35.3	0.14
I-277 / Kenliworth Ave	3	3	1	0	1	5	7	17	160	0.69	7.3	11.8	0.13
I-277 / US-74	2	2	1	0	1	5	7	12	82	1.32	2.3	11.8	0.13
I-485 / Lawyers Rd	1	1	1	0	0	0	0	22	53	2.13	0.1	23.5	0.23
I-485 / Idlewild Rd	3	2	2	0	0	0	4	33	102	1.71	0.1	23.5	0.23
I-485 / Old Monroe Rd	3	3	3	0	0	1	4	20	91	1.14	0.1	23.5	0.23
I-485 / Rea Rd	3	3	3	0	0	0	10	22	32	>10	0.1	23.5	0.23
I-485 / NC-51	3	3	3	0	0	2	11	36	151	1.44	0.4	23.5	0.23
I-485 / Pineville Rd	2	3	1	0	0	4	21	103	412	1.35	0.1	23.5	0.23
US-64 / S New Hope Rd	2	2	1	0	0	0	1	2	5	4.50	0.3	10.4	0.22
US-64 / Hudge Rd	2	2	1	0	0	0	0	2	6	1.50	0.2	10.4	0.22
US-64 / Smithfield Rd	2	1	1	0	0	0	0	3	12	1.00	0.2	10.4	0.22
US-64 / Eagle Rock Rd	2	1	3	0	0	0	0	4	15	1.09	0.2	10.4	0.22
US-64 / Rolesville Rd	3	1	3	0	0	5	6	26	108	1.56	0.1	10.4	0.22
US-64 / Lizard Lick Rd	3	1	3	0	0	2	6	26	105	1.44	0.1	10.4	0.22
US-70 / Tuscarora Rhems Rd	2	1	3	0	0	0	2	13	25	4.50	0.1	11.1	0.26
US-70 / US-17 Bypass	3	3	1	0	0	0	0	0	2	0.00	0.1	11.1	0.26
US-70 / NC-43	3	3	1	0	0	0	0	0	0		0.1	11.1	0.26
US-70 / Glenburnie Rd	2	2	2	0	0	0	0	0	0		0.2	11.1	0.26
US-70 / US-70 Business Rd	1	1	1	0	0	0	0	0	0		0.9	11.1	0.26
US-74 / NC216	1	1	1	1	1	0	1	8	29	1.83	0.2	22.8	0.09

Note:
K, A, B, C and O are fatal, injury type "A", "B" and "C" and PDO crashes, respectively.
1, 2, 3 for acceleration lane length and deceleration lane length indicate < 250 feet, 250 to 750 feet and > 750 feet, respectively.
1, 2, 3 for signboard placement distance indicate < 1,320 feet, 1,320 to 2,640 feet and 2,640 to 5,280 feet, respectively.
LI, %HV and RVR are luminour index, % heavy vehicles and ramp volume ratio, respectively.

Table 43. Interchanges without Lighting Systems – Data Summary

It is important that the affects of the above parameters are analyzed using data collected prior to identifying weight factors and updating the lighting priority index tool.

6.2.4. Define Categories and Ratings for Each New Factor

As a next step, categories and ratings are defined for each new factor identified in the previous step.

Acceleration Lane Length

Acceleration lane is the lane used to merge into the freeway traffic flow from an onramp at the interchange. Sufficient acceleration lane length is required so as to avoid any collision between through freeway traffic and merging onramp traffic. The acceleration lane length generally varies based on the posted speed limit of the facility being accessed. An acceleration lane length of 750 ft is generally considered adequate for design purposes. The acceleration lane lengths were therefore divided into three categories: 0 to 250 ft, 250 ft to 750 ft and greater than 750 ft.

The 0 to 250 ft acceleration lane length is the most critical situation. Hence, it was given a rating of 5 in the updated lighting priority index tool. The 250 ft to 750 ft acceleration length is relatively safer than 0 to 250 ft acceleration lane length and was given a rating of 3. As greater than 750 ft acceleration lane length is safest, it was given a rating of 1.

Deceleration Lane Length

Deceleration lane is the lane used to diverge from the freeway traffic flow to the offramp of the interchange. Sufficient deceleration lane length is required to avoid any collision between the diverging traffic and through freeway traffic, and also to avoid run-off road crashes and crashes involving fixed objects. The deceleration lane length depends on the posted speed limit of the mainline and offramp. A deceleration lane length of 750 ft is generally considered adequate for design purposes. Therefore, the deceleration lane lengths were divided into three categories: 0 to 250 ft, 250 ft to 750 ft and greater than 750 ft.

The 0 to 250 ft deceleration lane length is the most critical situation. Hence, it was given a rating of 5 in the updated lighting priority index tool. The 250 ft to 750 ft deceleration length is relatively safer than 0 to 250 ft deceleration lane length and was given a rating of 3. As greater than 750 ft deceleration lane length is safest, it was given a rating of 1.

Signboard Placement from the Interchange

The placement of signboard has an effect on diverging maneuver and safety at interchanges. A distance of 1-mile for signboard placement from the interchange is generally considered adequate for design purposes. If the signboard is placed at a distance less than 1-mile from the interchange, the time available for the driver to identify the path and make a decision to diverge from the freeway traffic is relatively less. The distance of signboard placement from the interchange was therefore divided into three categories: 0 to 1,320 ft, 1,320 ft to 5,280 ft and greater than 5,280 ft.

The signboard placement distance greater than 5,280 ft is considered safest and was given a rating of 1. The signboard placement distance category 2,640 ft to 5,280 ft is relatively unsafe and was given a rating of 3 while signboard placement distance category 0 to 1,320 ft is more unsafe and was given a rating of 5.

Crash Severity

The severity of injury resulting from a crash can significantly influence safety and risk analysis. Societal crash costs and quality of life impacts for high severity crashes are significantly higher than those associated with PDO and low severity crashes. The consideration of crash severity as part of an evidence/data driven analytical approach can complement and improve upon traditional crash frequency and crash rate methods. A mechanism to include and account for crash severity in North Carolina's interchange lighting warrants and prioritization tools can improve lighting decisions and investment performance.

Crash data were categorized into three categories: fatal and injury type “A”, injury types “B” and “C” and PDO. The maximum number of fatal and injury type “A” crashes at the selected 80 interchanges from 2006 to 2011 is 3. The fatal crashes were hence divided into three categories. Three or more fatal and injury type “A” crashes was given a rating of 5. One or two fatal and injury type “A” crashes was given a rating of 3 while 0 fatal and injury type “A” crash was given a rating of 1.

The average number of injury type “B” and “C” crashes at the selected 80 interchanges from 2006 to 2011 is equal to 10. Therefore, injury type “B” and “C” crashes were categorized as 0 to 10, 10 to 20, 20 to 30, 30 to 40 and >40 with ratings of 1, 2, 3, 4 and 5, respectively. Likewise, the average number of PDO crashes at the selected 80 interchanges from 2006 to 2011 is equal to 20. Therefore, PDO crashes were categorized as 0 to 20, 20 to 40, 40 to 60, 60 to 80 and >80 with ratings of 1, 2, 3, 4 and, 5 respectively.

Illuminance

Illuminance or level of lighting plays a vital role on visibility at night. An illuminance index equal to 0.7 footcandle is considered adequate while inadequate level increases risk to drivers under night-time conditions. The illuminance index was therefore divided into three categories: less than 0.4 footcandle, 0.4 footcandle to 0.7 footcandle and greater than 0.7 footcandle. An illuminance index less than 0.4 footcandle was given a rating of 5 while illuminance index 0.4 footcandle to 0.7 footcandle was given a rating of 3. The rating was given as 1 if illuminance index is greater than 0.7 footcandle.

Percent of Heavy Vehicle Volume

The percent of heavy vehicles has a bearing on operational performance and safety. Traffic data observed indicates that, on average, 25% of night-time traffic volume is heavy vehicles at the selected interchanges. The percent of heavy vehicles was categorized as 0 to 10%, 10% to 20%, 20% to 30%, 30% to 40% and greater than 40% with ratings of 1, 2, 3, 4 and 5, respectively.

Ramp Volume Ratio

Ramp volume ratio is the ratio of the number of vehicles merging or diverging to freeway through traffic volume. The ramp volume ratio was categorized as 0 to 0.1, 0.1 to 0.2, 0.2 to 0.3, 0.3 to 0.4 and greater than 0.4 with ratings of 1, 2, 3, 4 and 5, respectively.

6.2.5. Analyze Crash Data to Determine Unlighted and Lighted Weights for Each New Factor

Crash data obtained from NCDOT was used to determine the effect of each factor on the number of crashes by light condition. The area within 300 ft from an onramp or offramp was considered as interchange influence area. Crashes occurring within 300 ft of both onramp and offramp of an interchange were therefore attributed to the interchange. These crashes within the interchange influence area could be due to merging, diverging or weaving maneuvers.

The crashes occurring within the interchange influence area are identified for all the 80 selected interchanges along the study corridors. Descriptive analysis was then conducted to tabulate these crashes by acceleration lane length, deceleration lane length, signboard placement from the interchange, crash severity, night-time heavy vehicle percentage and ramp volume ratio. “C”, “P” and “No” in tables 44 to 46 indicate complete, partial and no freeway lighting, respectively.

Acceleration Lane Length

The number of crashes at each selected interchange was processed and summarized for 0 to 250 ft, 250 ft to 750 ft and greater than 750 ft acceleration lane length categories. Table 44 shows the number of crashes, interchanges and crashes per interchange by light condition and acceleration lane length categories.

From Table 44, the number of crashes decreased as the acceleration lane length increased. Moreover, the number of night-time crashes under unlighted (dark) conditions is greater than the number of crashes under lighted conditions in case of no freeway lighting. This implies that roadway lighting with sufficient acceleration lane length could reduce the number of crashes at interchanges.

As the number of crashes is highest for 0 to 250 ft acceleration lane length category, the lighted and unlighted weights for acceleration lane length were determined based on the number of crashes per interchange by light condition for this category. The lighted weight was considered as 1. The unlighted weight was computed as the number of night-time crashes per interchange without lighting for 0 to 250 ft acceleration lane length category divided by the number of night-time crashes per interchange with complete lighting for the same category plus 1. Based on computations, the unlighted weight is 2.07 whereas the lighted weight is 1.00 for acceleration lane length category.

Acceleration Lane Length (ft)	Freeway Lighting	# Night-time Crashes under Lighted Condition	# Night-time Crashes under Unlighted Condition	# Interchanges	# Night-time Crashes per Interchange under Lighted Condition	# Night-time Crashes per Interchange under Unlighted Condition
<250	C	352	298	14	25.14	21.29
	P	389	354	12	32.42	29.50
	No	131	509	19	6.89	26.79
250-750	C	98	138	6	16.33	23.00
	P	139	155	2	69.50	77.50
	No	39	311	12	3.25	25.92
>750	C	50	13	2	25.00	6.50
	P	58	69	2	29.00	34.50
	No	107	490	16	6.69	30.63

Table 44. Night-time Crashes by Light Condition and Acceleration Lane Length

Deceleration Lane Length

The number of crashes at each selected interchange was processed and summarized for 0 to 250 ft, 250 ft to 750 ft and greater than 750 ft deceleration lane length categories. Table 45 shows the number of crashes, interchanges and crashes per interchange by light condition and deceleration lane length categories.

From Table 45, the number of crashes decreased as the deceleration lane length increased. Moreover, the number of night-time crashes under unlighted (dark) conditions is greater than the number of crashes under lighted conditions in case of no freeway lighting. This implies that roadway lighting with sufficient deceleration lane length could reduce the number of crashes at interchanges.

Deceleration Lane Length (ft)	Freeway Lighting	# Night-time Crashes under Lighted Condition	# Night-time Crashes under Unlighted Condition	# Interchanges	# Night-time Crashes per Interchange under Lighted Condition	# Night-time Crashes per Interchange under Unlighted Condition
<250	C	415	361	18	23.06	20.06
	P	569	539	15	37.93	35.93
	No	173	952	36	4.81	26.44
250-750	C	85	88	4	21.25	22.00
	P	17	39	1	17.00	39.00
	No	57	230	6	9.50	38.33
>750	C	0	0	0		
	P	0	0	0		
	No	47	128	5	9.40	25.60

Table 45. Night-time Crashes by Light Condition and Deceleration Lane Length

As the number of crashes is highest for 0 to 250 ft deceleration lane length category, the lighted and unlighted weights for deceleration lane length were determined based on the number of crashes per interchange by light condition for this category. The lighted weight was considered as 1. The unlighted weight was computed as the number of night-time crashes per interchange without lighting for 0 to 250 ft deceleration lane length category divided by the number of night-time crashes per interchange with complete lighting for the same category plus 1. Based on computations, the unlighted weight is 2.15 whereas the lighted weight is 1.00 for deceleration lane length category.

Signboard Placement from the Interchange

The number of crashes at each selected interchange was processed and summarized for 0 to 1,320 ft, 1,320 ft to 5,280 ft and greater than 5,280 ft signboard placement distance categories. Table 46 shows the number of crashes, interchanges and crashes per interchange by light condition and signboard placement distance categories.

Sigh Board Placement Distance (ft)	Freeway Lighting	# Night-time Crashes under Lighted Condition	# Night-time Crashes under Unlighted Condition	# Interchanges	# Night-time Crashes per Interchange under Lighted Condition	# Night-time Crashes per Interchange under Unlighted Condition
<1320	C	387	300	19	20.37	15.79
	P	538	534	13	41.38	41.08
	No	229	1009	37	6.19	27.27
1320-2640	C	113	149	3	37.67	49.67
	P	44	44	2	22.00	22.00
	No	41	216	5	8.20	43.20
2640-5280	C	0	0	0		
	P	4	0	1	4.00	
	No	7	85	5	1.40	17.00

Table 46. Night-time Crashes by Light Condition and Signboard Placement

From Table 46, the number of crashes decreased as the signboard placement distance increased. Moreover, the number of night-time crashes under unlighted (dark) conditions is greater than the number of crashes under lighted conditions in case of no freeway lighting. This implies that roadway lighting with sufficient signboard placement distance could reduce the number of crashes at interchanges.

As the number of crashes is highest for 0 to 1,320 ft signboard placement distance category, the lighted and unlighted weights for signboard placement distance were determined based on the number of crashes per interchange by light condition for this category. The lighted weight was considered as 1. The unlighted weight was computed as the number of night-time crashes per interchange without lighting for 0 to 1,320 ft signboard placement distance category divided by the number of night-time crashes per interchange with complete lighting for the same category plus 1. Based on computations, the unlighted weight is 2.34 whereas the lighted weight is 1.00 for signboard placement distance category.

Crash Severity

The crash data was processed and categorized into three categories: fatal and injury type "A", injury types "B" and "C" and PDO. Table 47 shows the number of crashes by light condition and severity categories.

From Table 47, the number of night-time crashes under unlighted (dark) conditions is greater than the number of crashes under lighted conditions for each severity type. This implies that roadway lighting could reduce the number of crashes at interchanges.

Crash Type	# Night-time Crashes under Lighted Conditions	# Night-time Crashes under Unlighted (Dark) Conditions
Fatal & injury type "A"	28	32
Injury types "B" & "C"	422	622
Property Damage Only (PDO)	889	1,634

Table 47. Night-time Crashes by Light Condition and Severity

NCDOT recommends using 74.8 for fatal and injury type "A" crashes, 8.4 for injury type "B" and "C" crashes and 1 for PDO crashes to compute equivalent PDO crashes. These weights for the three crash severity categories were used to define warranting points for safety factor in the updated tool. Accordingly, a maximum of 30 points, 10 points and 1.5 points are proposed to be allocated for fatal and injury type "A" crashes, injury type "B" and "C" crashes and PDO crash categories, respectively. The sum (30 + 10 + 1.5 = 41.5) is relatively close to the maximum of 40 points allotted for safety factor in the current warranting tool. It should be noted that maximum warranting points are allocated if rating is equal to 5.

Different scaling levels (100, 10 and 1) were used for the three crash categories to allocate the points. Lighted and unlighted weights were computed for each severity category. The unlighted weight for fatal and injury type “A” crash category was computed as 100 times the number of unlighted fatal and injury type “A” crashes divided by the total number of fatal and injury type “A” crashes at the selected interchanges. Lighted weight was computed by subtracting the unlighted weight from 100. Based on computations, the unlighted weight is 53 whereas the lighted weight is 47 for fatal and injury type “A” crash category. Multiplying 53 minus 47 with a rating of 5 gives 30 warranting points (maximum) for this crash severity category.

The unlighted weight for injury type “B” and “C” crash category was computed as 10 times the number of unlighted injury type “B” and “C” crashes divided by the total number of injury type “B” and “C” crashes at the selected interchanges. Lighted weight was computed by subtracting the unlighted weight from 10. Based on computations, the unlighted weight is 6 whereas the lighted weight is 4 for injury type “B” and “C” crash category. Multiplying 6 minus 4 with a rating of 5 gives 10 warranting points (maximum) for this crash severity category.

The unlighted weight for PDO crashes was computed as the number of PDO crashes divided by the total number of PDO crashes at the selected interchanges. Lighted weight was computed by subtracting the unlighted weight from 1. Based on computations, the unlighted weight is 0.65 and lighted weight is 0.35 for PDO crash category. Multiplying 0.65 minus 0.35 with a rating of 5 gives 1.5 warranting points (maximum) for this crash severity category.

Illuminance Index, Percent of Heavy Vehicle Volume and Ramp Volume Ratio

The crash data was processed and summarized for each study corridor based on light condition. Table 48 shows the number of crashes by light condition. It also includes total number of crashes and crashes per interchange by lighting condition. The unlighted weight was computed by dividing the total number of night-time crashes under inadequate light conditions by the total number of night-time crashes. The lighted weight was computed by subtracting the unlighted weight from 1. Based on computations, the unlighted weight is 0.72 and lighted weight is 0.28 for illuminance level, percent of heavy vehicle volume and ramp volume ratio.

Table 49 summarizes lighted and unlighted weights for all selected factors.

Corridor	**# Night-time Crashes under Lighted Conditions**	**# Night-time Crashes under Unlighted (Dark) Conditions**
I-277	108	27
I-40	5	153
I-485	40	659
I-77	415	626
I-95	116	92
I-85	490	988
US-64/264	12	311
US-70	1	95
US-74	16	136
Total	1,203	3,087
Per interchange	15.04	38.59
%	28%	72%

Table 48. Total Lighted and Unlighted Night-time Crashes

Factor	**Unlighted Weight**	**Lighted Weight**
Deceleration Lane Length	2.07	1
Acceleration Lane Length	2.15	1
Signboard Placement	2.34	1
Crash Severity		
Fatal and Injury Type "A"	53	47
Injury Type "B" and "C"	6	4
PDO	0.65	0.35
Illumination	0.72	0.28
% Heavy Vechiles	0.72	0.28
Ramp Volume Ratio	0.72	0.28

Table 49. Summary of Lighted and Unlighted Weights

6.2.6. Update Interchange Lighting Priority Index Tool

The current warranting points tool shown in Table 38 was updated by including the new factors discussed in the previous steps, their categories and ratings, and, unlighted and lighted weights. Table 50 shows the updated interchange warranting condition tool.

6.3. Current and Updated Lighting Priority Index Tool – Comparison of Results

The interchange lighting priority index was computed by dividing the product of warranting points and benefit factor (25% of ADT) by the cost factor. The cost of construction of roadway lighting and energy consumption of roadway lights at each interchange was obtained from NCDOT. Benefits factor was computed as 25% of ADT obtained from NCDOT travel maps.

Table 51 shows warranting points and TDP priority index using current and updated lighting priority index tool for selected interchanges with lighting system. Figure 4 shows warranting points from current and updated lighting priority index tool for selected interchanges with lighting system while Figure 5 shows TDP priority indices from current and updated lighting priority index tool for the same set of interchanges with lighting system.

Table 52 shows warranting points using current and updated lighting priority index tool for selected interchanges without lighting system. Figure 6 shows warranting points from current and updated lighting priority index tool for selected interchanges without lighting system. TDP priority index could not be computed for these intersections due to lack of details pertaining to cost estimates.

TABLE B

INTERCHANGE SECTIONS

TIP PROJECT#: LI-0071 | COUNTY: | YEAR: 2012

ROADWAY SECTION: I1: I77/I277 Interchange

STATION FROM: N/A | STATION TO: N/A | LENGTH: N/A

PLACE AN "X" UNDER THE CORRESPONDING RATING #

CLASSIFICATION FACTOR		RATING					UNLIGHTED WEIGHT	LIGHTED WEIGHT	DIFFERENCE	RATING x DIFFERENCE
		1	2	3	4	5	(A)	(B)	(A-B)	
GEOMETRIC FACTORS										
1-GF	RAMP TYPES	DIRECT	DIAMOND	BUTTON HOOKS CLOVERLEAFS	TRUMPET	SCISSORS AND LEFT SIDE EXIT	2	1	1	2
			X							
2-GF	CROSSROAD CHANNELIZATION	NONE		CONTINUOUS		AT INTERCHANGE INTERSECTIONS	2	1	1	3
				X						
3-GF	FRONTAGE ROADS	NONE		ONE-WAY		TWO-WAY	1.5	1	0.5	0.5
		X								
4-GF	FREEWAY LANE WIDTH	12		11		10	3	2.5	0.5	0.5
		X								
5-GF	FREEWAY MEDIAN WIDTH	>40'	24-40'	12-24'	4-12'	<4'	1	0.5	0.5	1.5
				X						
6-GF	# FREEWAY LANES	4 OR LESS		6		8 OR MORE	10	8	2	10
						X				
7-GF	MAIN LANE CURVES	1/2	1-2	2-3	3-4	4	10	8	2	2
		X								
8-GF	GRADES	3%	3-3.9%	4-4.9%	5-6.9%	>7%	3.2	2.8	0.4	0.4
		X								
9-GF	SIGHT DIST. CROSS ROAD INTERSECTION	1000'	700-1000'	500-700'	400-500'	<400'	2	1.8	0.2	0.2
		X								
10-GF	ACCELERATION LANE	>750		250-750		<250	2.07	1	1.07	1.07
		X								
	DECELERATION LANE	>750		250-750		<250	2.15	1	1.15	1.15
		X								
11-GF	SIGNBOARD PLACEMENT	2640-5280		1320-2640		<1320	2.34	1	1.34	6.7
						X				
									SUBTOTAL	29.02
OPERATIONAL FACTORS										
1-OF	LEVEL OF SERVICE	A	B	B-C	C-D	D-E	6	1	5	10
			X							
2-OF	TOTAL NIGHT VOLUME PER LANE	<1000	1000	2000	3000	4000	6	1	5	20
					X					
3-OF	NIGHT RAMP VOLUME RATIO	0.0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	>0.4	0.72	0.28	0.44	2.2
						X				
4-OF	NIGHT % HEAVY VEHICLES	0-10%	10-20%	20-30%	30-40%	>40%	0.72	0.28	0.44	0.44
		X								
									SUBTOTAL	32.64
ENVIRONMENTAL FACTORS										
1-EF	%DEVELOPMENT	NONE	1 QUAD	2 QUAD	3 QUAD	4 QUAD	2	0.5	1.5	7.5
						X				
2-EF	OFFSET TO DEVELOP. FROM TRAFFIC LANES	>200'	150-200'	100-150'	50-100'	<50'	0.5	0.3	0.2	0.2
		X								
3-EF	CROSS ROAD APPROACH LIGHTING	NONE		PARTIAL		COMPLETE	3	2	1	3
				X						
4-EF	FREEWAY LIGHTING	NONE		INTERCHANGES ONLY		CONTINUOUS	5	3	2	6
				X						
5-EF	LUMINOUS INTENSITY	>0.7		0.4-0.7		<0.4	0.72	0.28	0.44	1.32
				X						
									SUBTOTAL	18.02
ACCIDENTS										
1-AF	NIGHT TIME CRASHES	0		1 to 2		3				41.5
	FATAL & A TYPE					X	53	47	6	30
		0-10	10 TO 20	20 TO 30	30 TO 40	>40				
	B & C TYPE					X	6	4	2	10
		0-20	20-40	40-60	60-80	>80				
	PDO TYPE					X	0.65	0.35	0.3	1.5
								INTERCHANGE WARRANTING CONDITION = 75 POINTS	TOTAL	121.18

Table 50. Updated Interchange Warranting Condition Tool

Interchange	Warranting Points (W)		Priority Index (PI)	
	Current	Updated (Night-time Crashes)	Current	Updated (Night-time Crashes)
I-77 / I-277	99	121	58	71
I-77 / Lassalle St	92	105	167	193
I-77 / NC-24	96	91	102	96
I-40 / Fines Creek Rd	76	74	20	19
I-85 / Cox Rd	97	98	192	195
I-95 / S Caton Rd	72	90	54	67
I-95 / N Roberts Ave	96	93	82	79
I-95 / Fayetville Rd	96	83	93	80
I-277 / S College St	99	84	108	92
I-277 / N Church St	91	86	169	162
I 485 / US-74	90	73	156	126
I-77 / W Morehead St	99	96	131	127
I-77 / W Trade St	104	129	142	176
I-77 / I-85	99	99	50	50
I-77 / NC-21 (Sunset Rd)	71	117	71	117
I-77 / I-485	79	76	30	29
I-77 / Gilead Rd	75	83	65	72
I-77 / NC-73 (Sam Furr Rd)	63	89	38	54
I-77 / Catabwa Ave	64	80	100	126
I-77 / Griffith Rd	67	84	89	111
I-85 / Edgewood Rd	58	74	84	108
I-85 / NC-274	96	94	140	136
I-85 / Sam Wilson Rd	105	108	141	145
I-85 / Little Rock Rd	97	105	77	84
I-85 / Mulbery Church Rd	80	112	74	104
I-85 / Tuckaseegee Rd	101	116	173	199
I-85 / NC-27	98	104	198	210
I-85 / Glenwood Drv	82	111	147	201
I-85 / NC-16	103	99	118	114
I-85 / Beattis Ford Rd	103	107	132	137
I-85 / Statesville Ave Rd	91	120	125	166
I-85 / N Graham St	87	101	238	277
I-95 / Carthage Rd	84	86	63	66
I-277 / I-77	111	85	64	49
I-277 / South Blvd	102	83	63	52
I-277 / NC-16	73	100	110	152
I-277 / N Caldwell St	103	86	79	66
I-277 / I-77	110	94	206	177

Table 51. Warranting Points and Priority Index for Interchanges with Lighting Systems

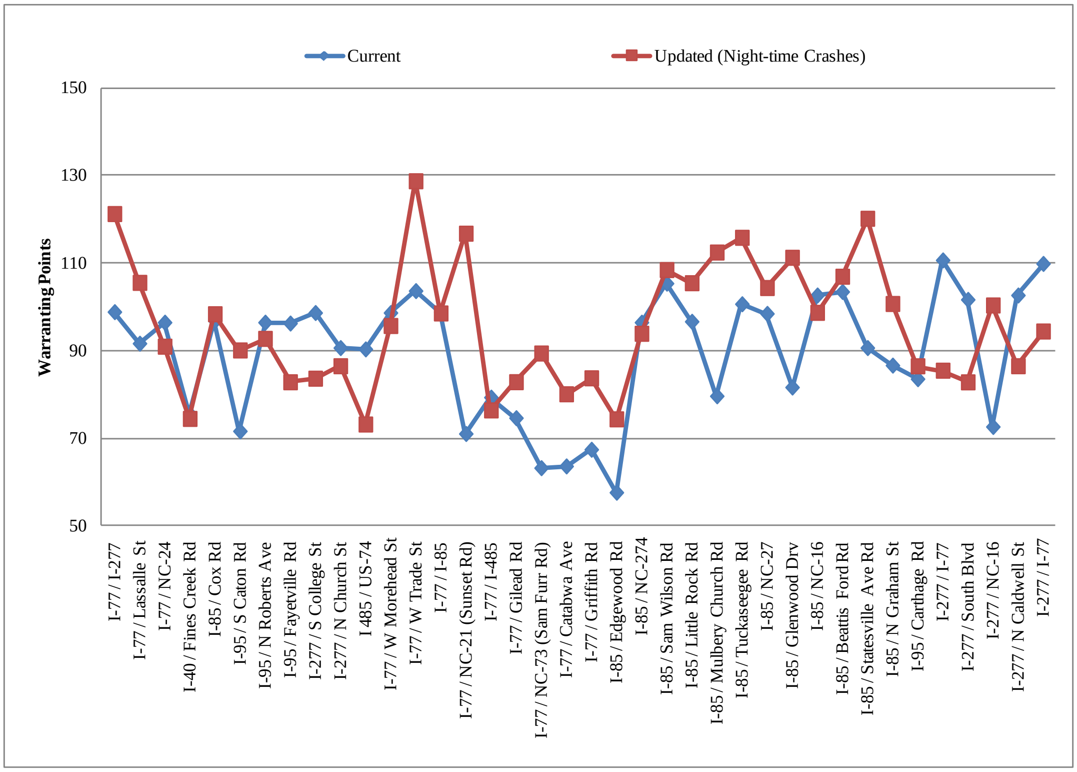

Figure 4. Warranting Points for Selected Interchanges with Lighting Systems

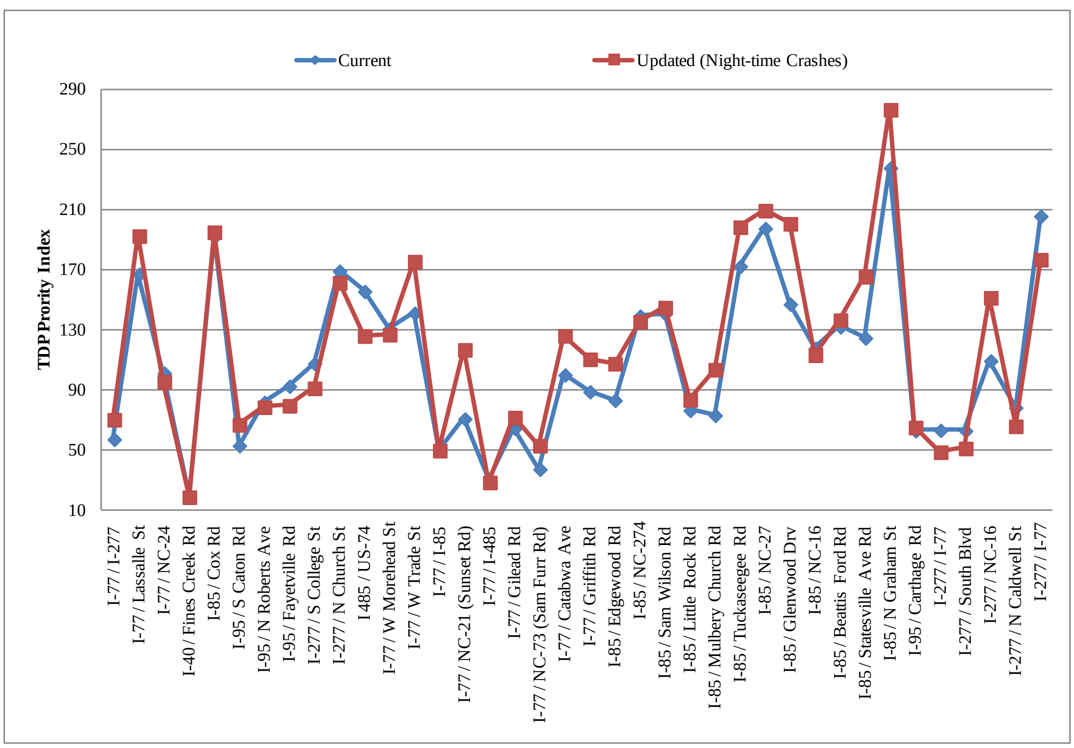

Figure 5. Priority Index for Selected Interchanges with Lighting Systems

Interchange	Warranting Points (W)	
	Current	Updated (Night-time Crashes)
I-40 / Cold Springs Creek Rd	80	71
I-85 / I-485	99	86
I-85 / I-77	98	103
I-485 / Providence Rd	75	80
I-485 / Johnston Rd	82	74
US-64 / I-540	89	64
US-64 / Knightdale Rd	85	68
US-64 / N Arendell Ave	77	71
US-70 / NC-41	74	60
US-70 / Clarks Rd	80	69
US-70 / Country Club Rd	62	75
US-74 / NC161	83	63
US-74 / Oak Grove Rd	81	73
US-74 / Shelby Rd	79	86
I-77 / W 5th St	100	122
I-85 / US-321	78	85
I-85 / NC-279	84	95
I-85 / S Main St	68	71
I-85 / NC-7	85	84
I-85 / McAdenville / N Main St	86	83
I-85 / NC-273	85	81
I-95 / US-301	81	89
I-277 / Kenliworth Ave	69	94
I-277 / US-74	102	108
I-485 / Lawyers Rd	87	78
I-485 / Idlewild Rd	93	75
I-485 / Old Monroe Rd	79	72
I-485 / Rea Rd	92	69
I-485 / NC-51	91	78
I-485 / Pineville Rd	89	86
US-64 / S New Hope Rd	94	78
US-64 / Hudge Rd	79	73
US-64 / Smithfield Rd	71	84
US-64 / Eagle Rock Rd	54	62
US-64 / Rolesville Rd	85	68
US-64 / Lizard Lick Rd	72	61
US-70 / Tuscarora Rhems Rd	74	57
US-70 / US-17 Bypass	44	59
US-70 / NC-43	48	60
US-70 / Glenburnie Rd	55	69
US-70 / US-70 Business Rd	57	80
US-74 / NC216	85	87

Table 52. Warranting Points and Priority Index for Interchanges without Lighting Systems

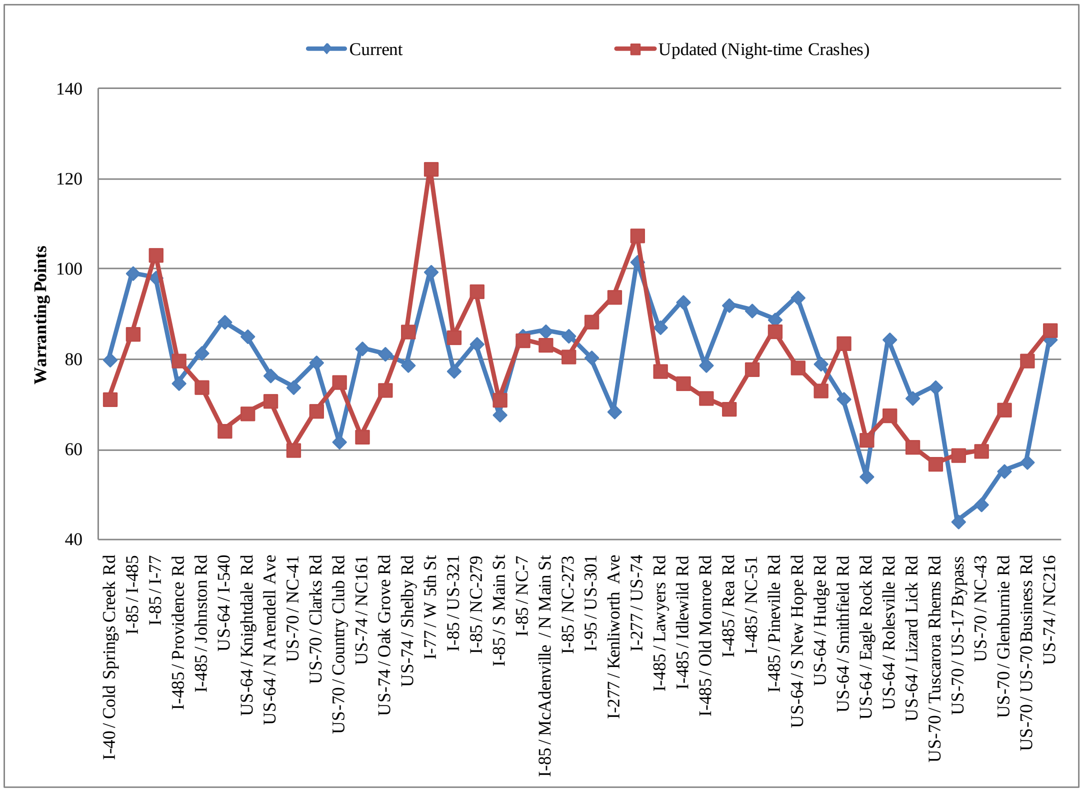

Figure 6. Warranting Points for Selected Interchanges without Lighting Systems

The warranting points computed using the updated tool with the additional factors was observed to be greater than warranting points computed using the current tool for 22 out of 38 selected interchanges with lighting system (Table 51). While 15 interchanges with lighting systems had computed warranting points from the updated tool less than computed values from the current tool, the computed warranting points was equal using current and updated tool for one interchange with a lighting system.

The night-time crashes were lower than the day-time crashes at 35 out of 38 interchanges with lighting systems. The night-to-day crash rate ratio was equal to 3, 3.13 and 4.5 (or night-to-day crash ratio was equal to 1, 1.04 or 1.5) for one interchange each with a lighting system. The interchange with night-to-day crash rate ratio (I-277 / I 77) equal to 4.5 had 0 fatal, 0 injury type “A”, 0 injury type “B”, 1 injury type “C” and 2 PDO night-time crashes while the total number of crashes observed at this interchange was equal to 5 (resulting in a night-to-day crash rate ratio of 4.5). On the other hand, I-77 / NC-21 (Sunset Rd) had 2 fatal, 2 injury type “A”, 5 injury type “B”, 35 injury type “C” and 84 PDO night-time crashes while the total number of crashes observed at this interchange was equal to 569 (resulting in a night-to-day crash rate ratio of 0.87). This clearly indicates that using night-to-day crash rate ratio instead of number of crashes by severity could result in biased allocations to interchanges with fewer numbers of crashes.

In the current lighting priority index tool, ratings 1, 2, 3, 4 and 5 are used for <1, 1 to 1.1, 1.1 to 1.2, 1.2 to 1.5 and >1.5 night-to-day crash rate ratio, respectively. As night-time crashes are generally lower than day-time crashes (< 1), fewer safety factors related warranting points are assigned to interchanges. On the other hand, the severity of crashes was considered in the updated tool. The weights were higher for fatal and severe injury crashes followed by less severe injury crashes and PDO crashes. The occurrence of severe crashes resulted in relatively higher warranting points using the updated tool for most of the interchanges with lighting systems. Interchanges such as I-77 / I-277, I-77 / W Trade Street, I-77 / NC-21 (Sunset Rd), I-85 / Tuckaseegee Rd, I-85 / Glenwood Drv and I-85 / Statesville Avenue Road with fatal and more injury crashes have not only seen an increase but more than 100 warranting points using the updated tool (when compared to the current tool). On the other hand, I-277 / I-77 has more than 100 warranting points using the current tool and seen a decrease in warranting points using the updated tool (due to fewer number of crashes). The computed priority indices for interchanges with lighting systems followed a trend similar to warranting points.

Table 52 shows the warranting points computed for the interchanges without lighting systems. The computed warranting points using the updated tool for 18 interchanges out of 42 selected interchanges without lighting systems was observed to be greater than warranting points computed from the current tool. This is primarily because of occurrence of severe crashes at these interchanges. The remaining 24 interchanges without lighting systems had computed warranting points from the updated tool less than computed values from the current tool.

Overall, 37 out of the 42 interchanges without lighting systems have a night-to-day crash rate ratio less than 3 (or night-to-day crash ratio less than 1). It was observed equal to 3 at one interchange, equal to 4.5 at two interchanges, equal to 6 at one interchange and a very high value at one interchange (all crashes occurred at night-time). While one interchange (US-64 / S New Hope Rd) with night-to-day crash rate ratio equal to 4.5 had 0 fatal, 0 injury type “A”, 0 injury type “B”, 1 injury type “C”, 2 PDO night-time crashes and 5 total crashes, the second interchange (US-70 / Tuscarora Rhems Rd) had 0 fatal, 0 injury type “A”, 0 injury type “B”, 2 injury type “C”, 14 PDO night-time crashes and 25 total crashes. The interchange (US-70 / NC-41) with night-to-day crash rate ratio equal to 6 had 0 fatal, 0 injury type “A”, 1 injury type “B”, 0 injury type “C” and 3 PDO night-time crashes while the total number of crashes observed at this interchange was equal to 6. On the other hand, I-277 / Kenilworth Ave had 0 fatal, 1 injury type “A”, 5 injury type “B”, 7 injury type “C” and 17 PDO night-time crashes and 160 total crashes with a night-to-day crash rate ratio equal to 0.69. Like in the case of analysis of interchanges with lighting systems, this clearly indicates that using night-to-day crash ratio could result in biased results (toward interchanges with fewer numbers of crashes).

Interchanges such as I-85 / I-77 and I-77 / W 5th St with fatal and more severe injury crashes have seen an increase and have more than 100 warranting points using the updated tool (when compared to the current tool). On the other hand, US-64 / S New Hope Rd has 94 warranting points using the current tool (primarily due to high night-to-day crash ratio) but seen a decrease in warranting points using the updated tool.

CHAPTER 7. CONCLUSIONS

Roadway lighting systems plays a vital role in reducing crashes during night-time and under adverse weather conditions. North Carolina has massive State owned lighting system spanning over 2,700 center-lane miles of full access controlled and partial access controlled facilities (comprising Interstate, US, NC and State secondary routes). It is important to update and maintain the existing roadway lighting systems, prioritize the locations based on safety factors and allocate the funds to serve the needs in the most beneficial manner. Research was therefore conducted to 1) develop an assessment report and summary of accumulated modernization / replacement needs, 2) assess current lighting needs and develop a method to allocate funds at NCDOT Division level, 3) research and document if installation of LED luminaires instead of HPS luminaires will yield benefits, 4) research privatization / outsourcing options, 5) research and develop an improved mechanism to prioritize interchange locations that require lighting, and, 6) recommend an improved warranting criteria with operational and performance measures. Conclusions from the study and plan for implementation are discussed next.

7.1. Conclusions

Data from Division level surveys conducted in 2005, and updated in spring 2011 and spring 2013 by staff of NCDOT were summarized to identify the number of interchanges where lighting systems exist, and if they were recently repaired, replaced or removed. Two methods were devised to perform a Division level assessment and assist in data driven allocation of resources between Divisions in North Carolina. The first method is based on percent population, the number of interchanges with lighting systems and the percent of night-time crashes on full access controlled and partial access controlled facilities whereas the second method is based on percent population, the number of interchanges with lighting systems and the percent of total crashes on full access controlled and partial access controlled facilities. Though as expected and similar in trends, marginal differences in funds allocated to the Divisions was observed based on the two methods. The allocation of resources is highest for Division 10 followed by Divisions 5 and 7. As lighting systems are more meant for night-time travel, method 1 based on night-time crashes is recommended for use rather than method 2 based on total crashes.

Results obtained from economic analysis comparing HPS and LED luminaires show that replacing 250 W HPS luminaires with up to 105 W LED luminaires would result in cost savings whereas replacing 400 W HPS luminaires with up to 215 W LED luminaires would result in cost savings. Economic benefits tend to decrease as wattage increased. It is recommended that LED luminaires with lowest wattage but provide equal effective lumens be identified and used to replace HPS luminaires.

In general, the life of HPS luminaires is 3 years while the life of LED luminaires is 12 years. During a 12 year period, HPS luminaires are installed once and relamped three times while LED luminaires are installed once. The personnel costs to install or replace lamps and delay costs due to disruption to traffic were ignored in the economic analysis. Further, the cost of LED luminaires may decrease while energy consumption costs generally increase over time. Considering these in economic analysis would make installation of LED luminaires more economically viable and cost-effective. The only disadvantage seems to be associated with trashing or recycling LED luminaires. However, it is expected that better solutions will be identified due to increasing use of LED luminaires in recent years to make this a relatively more eco-friendly option as well. Moreover, unlike HPS lamps, LED luminaires does not contain mercury.

An economic analysis comparing various PPP options for design, construction and maintenance of roadway lighting systems was conducted. Results obtained indicate that current practice of roadway lighting design and maintenance by NCDOT and construction by private firms is an equally viable option as maintenance by NCDOT and roadway lighting design and construction by private firms. It is therefore recommended that NCDOT should continue with their current practice i.e., design and maintenance of the lighting system by NCDOT and construction by private firms or contractors.

Roadway lighting design by NCDOT and construction and maintenance by private firms is as economical as privatizing design, construction and maintenance of roadway lighting systems. Results from sensitivity analysis support those obtained from economic analysis. While results are insensitive to changes in design and maintenance cost, they, as expected, seem to be more sensitive to construction costs. Obtaining competitive bids and lowering private firm construction cost will lower the overall cost and maximize benefits to NCDOT.

NCDOT currently performs lighting evaluations in accordance with the “Total Design Process (TDP)” adopted from NCHRP Report 152 “Warrants for Highway Lighting”. The warranting points are computed using various geometric factors, operational factors, environmental factors and night-to-day crash rate ratio. Data was collected at 80 interchanges (38 with lighting systems and 42 without lighting systems) along nine corridors to identify new factors, unlighted and lighted weights and update the “Total Design Process (TDP)” prioritization tool. The new factors identified include acceleration lane length, deceleration lane length, distance of signboard placement from the interchange, crashes by severity, illumination level, the percent of heavy vehicles at night and ramp volume ratio. Acceleration lane length and deceleration lane length less than 250 ft, signboard placement distance less than 1,320 ft, lower illuminance levels, and increase in percent of heavy vehicles and ramp volume ratio all tend to increase risk to drivers at interchanges.

Analysis based on crash data indicate that night-to-day crash rate ratio is less than 3 (or night-to-day crash ratio is less than 1) for 35 interchanges with lighting systems and 37 interchanges without lighting systems. It was observed to be greater than 3 at one interchange with a lighting system and three interchanges without lighting systems. These interchanges with night-to-day crash rate ratio greater than 3 have relatively fewer numbers of crashes. Also, most of the crashes at interchanges with night-to-day crash rate ratio greater than 3 are less severe injury or PDO crashes. A comparison of computing points using current and updated tool indicates a decrease in warranting points at these interchanges using the updated tool. In general, warranting points increased and are higher based on updated tool for interchanges with more severe crashes. Therefore, it is recommended to consider the number of crashes by severity instead of night-to-day crash rate ratio for prioritization using the TDP.

7.2. Implementation Plan

The outcomes and findings from this project can be implemented in several ways. The method to allocate limited resources to address existing lighting needs at Division level can be used along with the maintenance estimates by Division based on the existing kilowatt-hour consumption of interchange lighting system.

The recommended LED luminaires could be used to replace HPS luminaires to achieve energy savings and reduce costs. The lighting prioritization tool can be used to evaluate lighting project candidates in advance of the Transportation Improvement Program (TIP) project schedule or requests from the Division.

7.3. Scope for Further Research

Providing lighting at obsolete sections because of no traffic at night, due to closure of business or change in land use is cost prohibitive. Field observations indicate that most businesses except gas stations along urban corridors at the selected interchanges are closed by 10 PM. The night-time traffic volume is less than 15% of ADT. This suggests that using 25% of ADT obtained from traffic forecasters in the Statewide Planning Branch may result in overestimating warranting points. A traffic data collection study and temporal analysis of the data is required to identify percent of night-time traffic volume and percent of heavy-vehicles during night-time. Using these percentages specific to North Carolina may yield a better estimate of lighting warranting points.

Possible dimming of lights after midnight based on percent ADT may reduce energy consumption costs and lead to economical benefits. However, the significant investment in equipment for dimming and trimming could result in a long payback period. Research on cost-effectiveness of dimming and trimming of roadway lighting, and when and where it is applicable merits an investigation.

Literature does not document a strong rational for selection of unlighted and lighted weights used for factors in the current tool. Also, correlation may exist between some of the factors used in the current tool. As an example, ramp volume may be correlated to percent development, while level-of-service may be correlated to night-time traffic volume. A research to verify and validate factors and weights in the current tool is therefore recommended.

Further, it is recommended that NCDOT conduct a field study to identify LED luminaires that produce visually effective lamp lumens equal to 250 W, 400 W and 750 W HPS luminaires currently used on full access controlled facilities in North Carolina.

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